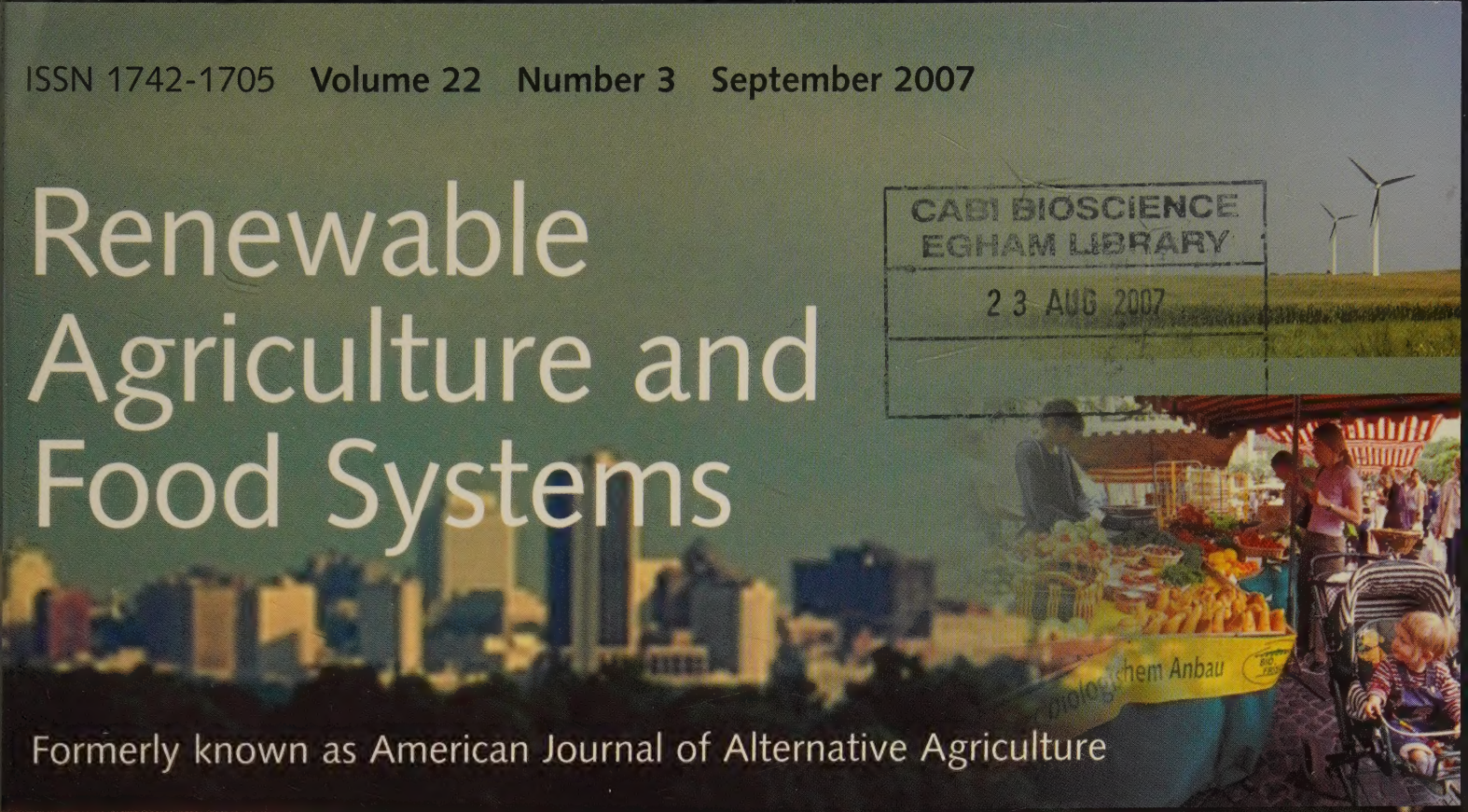
ISSN 1742-1705 **Volume 22 Number 3 September 2007**

Renewable Agriculture and Food Systems

CABI BIOSCIENCE
EGHAM LIBRARY
23 AUG 2007

Formerly known as American Journal of Alternative Agriculture



CAMBRIDGE
UNIVERSITY PRESS

Renewable Agriculture and Food Systems

Editor-in-Chief
John W. Doran, USDA–ARS, 116 Keim Hall, University of Nebraska, Lincoln, NE 68583-0934, USA
Email: rafjournal@cambridge.org

Forum and Resources Review Editors
Fred Kirschenmann, Leopold Ctr. For Sustainable Ag., Iowa State University, Ames, USA.
Email: leopold1@iastate.edu
Mark Liebig, USDA-ARS, Mandan, ND, North Dakota, USA.
Email: mark.liebig@ars.usda.gov

Associate Editors
Molly Anderson, Consultant, Massachusetts, USA
Kathleen Delate, Iowa State University, USA
Martin H. Entz, University of Manitoba, Canada
Gail Feenstra, Sustainable Agri. Res. & Educ. Program, UC Davis, USA
Charles A. Francis, University of Nebraska, USA
Alan Franzluebbers, USDA–ARS, Georgia, USA
Athanasios Gertsis, American Farm School, Greece
Peter R. Grace, Queensland University of Technology, Australia
Jonathan Halvorson, USDA–ARS, West Virginia, USA
Cinthia Johnson, Plainview Farms, Colorado, USA
Ulrich Köpke, Bonn University, Germany
Tom Larson, Farmer, Nebraska, USA
Don Lotter, Imperial Valley College, CA, USA
Stephen R. Moore, North Carolina A & T, USA
Urs Niggli, FiBL, Frick, Switzerland
Dicle Oguz, Ankara University, Turkey
Margaret Roper, CSIRO Plant Industry, Australia
John Ryan, ICARDA, Syria
Ilkden Talay, Ankara University, Turkey
Raymond R. Weil, University of Maryland, USA
Rick Welsh, Clarkson University, Potsdam, NY, USA

Submission of Manuscripts
Manuscripts should be submitted via our online manuscript submission and tracking site, **www.edmgr.com/rafs**.
Full instructions for electronic submission are available directly from this site and from www.journals.cambridge.org/jid_RAF.
To facilitate rapid reviewing, communications for peer review will be electronic and authors will need to supply a current e-mail address when registering to use the systems.

Full Notes for Authors are available from:
www.journals.cambridge.org/jid_RAF, and an abbreviated version is printed at the back of this issue.

Subscriptions
Renewable Agriculture and Food Systems (ISSN 1742-1705) is published four times a year in March, June, September and December. The subscription price for institutions of Volume 22 (2007) which includes electronic access and delivery by air is £143 (US $262 in the USA, Canada and Mexico); the electronic only price for institutions is £110 (US $199 in the USA, Canada and Mexico). Single parts are £36 (US $66 in the USA, Canada and Mexico), plus postage.

Orders, which must be accompanied by payment, may be sent to a bookseller, subscription agent or direct to the publisher: Cambridge University Press, The Edinburgh Building, Shaftesbury Road, Cambridge CB2 8RU, UK; or in the USA, Canada and Mexico: Cambridge University Press, Journals Fulfillment Department, 100 Brook Hill Drive, West Nuack, New York, 10994-2133. EU subscribers (outside the UK) who are not registered for VAT should add VAT at their country's rate. VAT registered subscribers should provide their VAT registration number. Japanese prices for institutions are available from Kinokuniya Company Ltd, P. O. Box 55, Chitose, Tokyo 156, Japan.

Copies of the journal for subscribers in the USA, Canada and Mexico are sent by air to New York to arrive with minimum delay. Periodicals postage paid at New York and at additional mailing offices. Postmaster: send address changes in the USA, Canada and Mexico to: *Renewable Agriculture and Food Systems,* Cambridge University Press, 100 Brook Hill Drive, West Nyack, New York 10994-2133. Claims for missing issues should be made immediately on receipt of the subsequent issue.

Advertising
Advertising queries for all parts of the world *except* the USA, Canada and Mexico to the Journals Advertising Co-ordinator: Rebecca Curtis, ad_sales@cambridge.org
Address enquiries in the USA, Mexico and Canada *only* to: journals_advertising@cup.org

Copying
This journal is registered with the Copyright Clearance Centre, 222 Rosewood Drive, Danvers, MA 01923, USA. Organizations in the USA who are also registered with C. C. C. may therefore copy material (beyond the limits permitted by sections 107 and 108 of U.S. Copyright law) subject to promotional or commercial purposes. Code 1742-1705/2007 $16.00. *ISI Tear Sheet Service,* 3501 Market Street, Philadelphia, PA 19104, USA is authorized to supply single copies of separate articles for private use only. Organizations authorized by the Copyright Licensing Agency may also copy material subject to the usual conditions. *For all other use*, permission should be sought from Cambridge or the American Branch of Cambridge University Press.

Renewable Agriculture and Food Systems is abstracted/indexed in Academic Search FullTEXT, AGRICOLA (Bibliography of Agriculture), AGRIS, Biological and Agricultural Index, CAB ABSTRACTS, Dietary Supplements (IDIS) Database, Environment Abstracts, Environmental Periodicals Bibliography, First Search (OCLC), Sociological Abstracts, Social Planning/Policy & Developmental Abstracts, Uncover

Internet Access
The online edition is available at: www.journals.cambridge.org/jid_RAF with free table of contents alerts (upon registration).

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Shaftesbury Road, Cambridge CB2 8RU, UK
32 Avenue of the Americas, New York, NY 10013-2473, USA
477 Williamstown Road, Port Melbourne VIC 3207, Australia

This journal is typeset and printed on acid-free paper from renewable sources
Printed by Latimer Trend, Plymouth, UK.

"Sustaining Earth and its People"

Scales image: Design, George Eisele, Lincoln, NE; artwork, Pat Scullion, ASA/CSSA/SSSA, Madison, WI, USA
Cover images: Farm/city landscape: © USDA Photo, Tim McCabe; Wind turbines in field: © John Doran; Farmers market: © BLE Bonn, Dominic Menzler; Cropping scene: © USDA Photo, Cole; Pasture & farm: © USDA Photo, Ron Nichols; Passion fruit farmer: © Manor House Agricultural Center, Kitale, Kenya

Renewable Agriculture and Food Systems: 22(3); 157–167 doi:10.1017/S1742170507001688

Does growing Canadian Western Hard Red Spring wheat under organic management alter its breadmaking quality?

H. Mason[1], A. Navabi[1], B. Frick[2], J. O'Donovan[3], D. Niziol[4], and D. Spaner[1,*]

[1]Department of Agricultural, Food, and Nutritional Science, University of Alberta, Edmonton, AB, T6G 2P5, Canada.
[2]Organic Agriculture Centre of Canada, c/o Department of Plant Sciences, University of Saskatchewan, 51 Campus Drive, Saskatoon, SK, S7N 5A8, Canada.
[3]Agriculture and Agri-Food Canada, Beaverlodge, AB, T0H 0C0, Canada.
[4]Agriculture and Agri-Food Canada, Winnipeg, MB, R3T 2M9, Canada.
*Corresponding author: dean.spaner@ualberta.ca

Accepted 12 September 2006 **Research Paper**

Abstract

Canadian Western Hard Red Spring (CWRS) wheat is recognized as premium quality wheat, ideal for breadmaking due to its superior milling qualities, baking characteristics and protein content. Organic wheat production is becoming more prevalent in Canada, due to increasing consumer demand for organic wheat products. Differences may exist in the baking and milling quality of wheat grown under conventional and organic management, a result of the dissimilarity between organic and conventional soil and crop management practices. Five CWRS cultivars released from 1885 to 1997 were grown under conventional and organic management and were assessed for their breadmaking potential. Several traits were investigated, including test weight, protein content, flour yield, kernel hardness and several mixograph parameters. Test weight was higher under conventional management, while no differences in protein content were observed between organic and conventionally grown wheat. Higher sodium dodecyl sulfate sedimentation (SDSS) volume, a reflection of gluten strength, was observed under conventional management, while there was a trend towards higher dough strength under organic management. Cultivars differed in grain protein, flour yield, kernel hardness and mixograph parameters, with Park and McKenzie superior to the others, particularly Red Fife, a much older cultivar. Management × cultivar interaction effects suggest that cultivars exhibit somewhat different baking characteristics when grown in the two management systems. There was no evidence that older cultivars (developed prior to the widespread use of pesticides and fertilizers) are better suited, in terms of breadmaking quality, for organic production.

Key words: *Triticum aestivum* L., organic agriculture, Canada, test weight, protein, mixograph, baking

Introduction

There are a number of factors used to evaluate bread quality, such as flavour, nutritional value, texture and color[1]. In combination with industrial processes (e.g., milling and baking), wheat flour properties, dough mixing abilities and loaf characteristics are determinants of bread quality[1]. These determinants can be further broken down into categories and are often evaluated in terms of breadmaking potential using a variety of tests (Figure 1).

Cultivars of the Canadian Western Hard Red Spring (CWRS) class of wheat are the most widely grown in western Canada; comprising about 83% of the hexaploid wheat area in the region, and generating $3 billion in gross revenue in 1998[2]. CWRS wheat is recognized as premium quality wheat, ideal for breadmaking due to its superior milling qualities, baking characteristics and protein content[3]. It is ideal for use in the production of high-volume pan breads, and it is commonly utilized, either alone or in mixture with weaker wheats, in the production of hearth breads, noodles, flat breads and steam breads[3]. A number of analytical procedures are used in the evaluation of each new CWRS cultivar in order to ensure conformity with Canadian industrial quality standards. The Canadian Grain Commission divides these tests into two main categories, (1) wheat tests, including protein content, test weight, flour

© 2007 Cambridge University Press

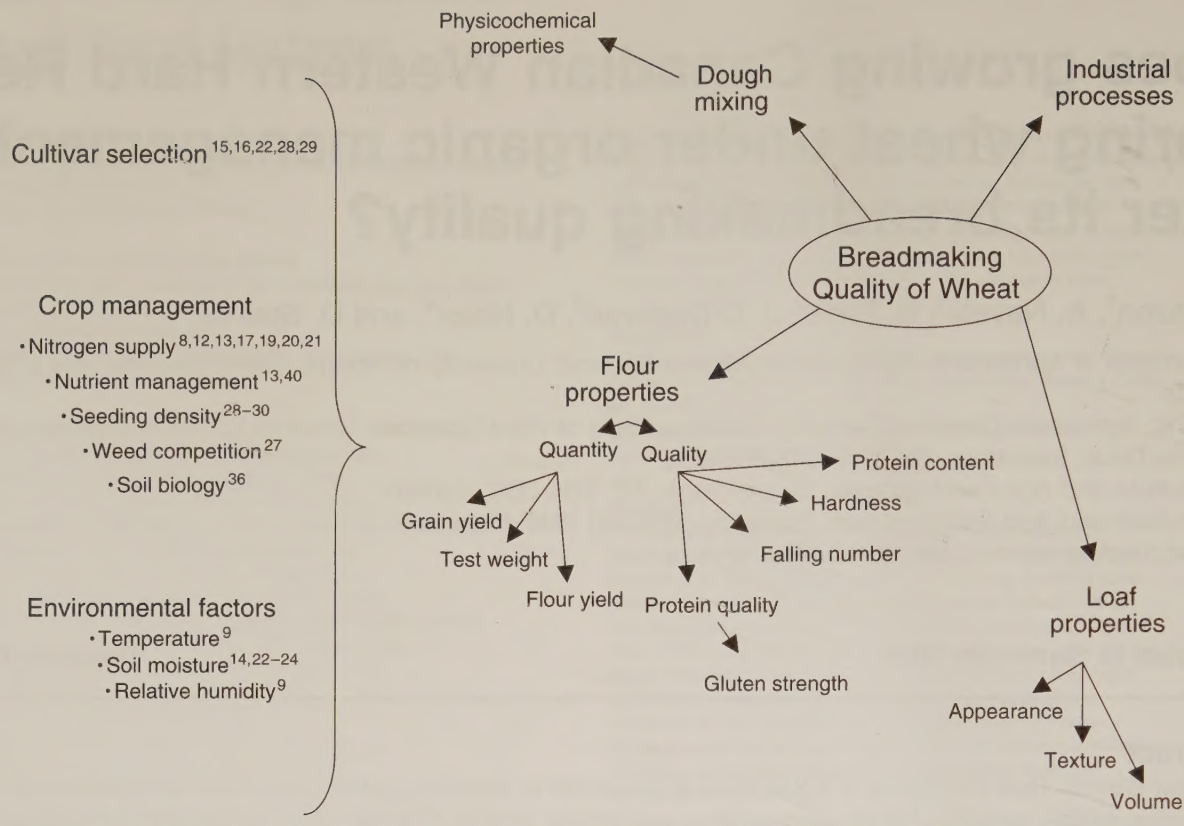


Figure 1. Flow chart describing components that determine breadmaking quality and mediating influences of cultivar selection, crop management and environmental factors.

yield, kernel hardness, falling number and sodium dodecyl sulfate sedimentation (SDSS), and (2) flour tests, including ash content, gluten index, extensigraph, amylograph, farinograph and mixograph tests[4].

Grain protein content is one of the main factors influencing wheat quality and is a valuable predictor of overall breadmaking quality[5,6]. It is the protein portion that gives the strength to the dough, allowing it to trap CO_2 gases produced during fermentation[7]. For breadmaking, protein contents ranging from 10.5 to 13.5% are most desirable[4]. Wheats with lower than 10% protein are often used for making cakes, cookies and crackers, or are blended with grain containing higher than 14% protein. Test weight is used to indicate the density and soundness of the wheat, and generally high test weights ($>75\,kg\,hl^{-1}$) are desirable. Flour yield is another important consideration and a simple measure of milling quality. A high flour yield is approx. 78%. Kernel hardness is usually expressed in terms of Particle Size Index (PSI). CWRS cultivars usually fall between 50 and 55 PSI. Harder kernels require more energy to break down into flour thereby increasing the amount of damaged starch granules in the flour, influencing gas production and flour water absorption. Falling number is an indicator of the sprouting resistance of the wheat. Sprouting can cause the release of large amounts of normally absent α-amylase into the kernel, ultimately altering its water holding properties. A falling number above 400 is indicative of a sound starch with little or no α-amylase present[4].

The SDSS test is used to distinguish wheat genotypes with superior gluten strength and is commonly referred to as an indicator of protein quality and overall end-use potential[8,9]. SDSS tests give a measure of high molecular weight proteins, mainly glutenins, present in wheat flour[7]. Sedimentation volumes range from 15 ml in wheat with weak gluten to 80 ml in wheats with strong gluten; CWRS wheats typically fall between 55 and 60 ml. The mixograph is one of many physical dough-testing instruments available in order to predict the behavior of dough mixing properties of wheat cultivars[10]. The mixograph tests the physico-chemical properties of dough, which are strongly related to gluten properties[4].

Grain protein content is the most commonly studied parameter of wheat quality. Both grain protein content and overall bread quality are affected by genotype and environment (e.g., year, temperature, rainfall and soil nutrient management)[6,11–14] (Figure 1). Fowler and De la Roche[15] reported significant differences among Canadian spring wheat cultivars for test weight, protein content, flour yield and for some mixograph parameters. Preston et al.[16]

reported genotypic differences in kernel hardness, protein content, and physical flour properties of CWRS wheats, and that environment had the largest effect on protein content. Similarly, Fowler and De la Roche[15] reported that the effect of environment was the main contributor to variation in yield and protein content in Canadian spring wheat. Variation among environments can be due to climatic and/or management factors. The most important management and climatic effects on protein content are nitrogen fertilizers and soil moisture[15,17,18]. Grain protein content of wheat is commonly reported to increase with applications of N fertilizer[8,17,19], and is lower in nitrogen-deficient soils. In addition to protein quantity, gluten strength (as measured by SDSS) has been positively influenced by increased N[8,13,19] and S[13] application. Several studies have reported that N fertilizer regimes that increased protein quantity also increased gluten strength[12,20,21]. Under moderate drought stress, grain protein concentrations have reportedly increased[14,22,23], yet tend to decrease under more extreme moisture deficits[24]. This increased protein under limited moisture is thought to be a result of altered starch and protein deposition in the grain, leading to an increase in the ratio of protein to starch[25]. Researchers in Spain reported that, in addition to protein content, test weight and gluten strength were higher under rainfed conditions compared to irrigated conditions[14]. Another climatic factor, heat stress, appears to be more variable in its effect on grain protein quantity, although it has been reported to have detrimental effects on protein and baking quality[9].

Organic cropping systems differ primarily from conventional systems because the use of mineral fertilizers and synthetic chemical pesticides are prohibited. Organic wheat production is becoming more prevalent in Canada, due to an increased consumer demand for organic wheat products. Differences may exist in the baking and milling quality of wheat grown under conventional and organic management, a result of the dissimilarity between organic and conventional soil and crop management practices. Soils of organically managed fields often have lower N levels than their conventional counterparts, which may influence organic grain protein content[26]. Aside from differences in soil N, organic and conventional systems often differ in terms of weed prevalence and diversity, and soil biology, which could influence competition for soil resources (i.e., nutrients and moisture) and stress tolerance. Mason and Madin[27] reported variable effects of weed competition on the grain protein content of wheat, while others have reported both improvements and declines in various wheat quality measures with changes in seeding rate[28–30]. This suggests that both inter- and intra-specific competition effects have the potential to affect wheat quality and should be further studied. The various inputs associated with organic management (e.g., crop residues and animal manure) can greatly increase the biological activity of a soil which can alter nutrient availability[31–33]. Burger and Jackson[31] reported that organic soils receiving inputs of composted manure and harvest residues had a higher N-supplying capacity than conventionally managed soils receiving mineral fertilizers and harvest residues. They also suggested that the supply of N in organic soils extended later in to the growing season than in the conventionally managed soil. In addition, mycorrhizal colonization of wheat has been found to be greater in soils under organic management when compared to conventionally managed soils, and has also been found to moderate yield losses commonly experienced by organic producers[34]. While mycorrhizae are known largely for their ability to assist in phosphorus uptake, there is evidence that mycorrhizal associations assist in the uptake of N in wheat[35,36].

Research investigating quality differences between organically and conventionally grown wheat has been conducted in some European nations; however there is no evidence of any research of this kind in Canada to date. Some researchers have observed that grain protein is higher in conventional systems than in organic[37–39] and biodynamic management systems[40], where no chemical fertilizers or pesticides were used. In contrast, Shier et al.[18] reported no differences in grain protein levels of spring wheat grown in organic and conventional cropping systems, which they attributed to adequate soil nutrient levels in both systems. Similarly, Ryan et al.[41] found no difference in grain nitrogen concentration between organic and conventional sites. Other studies, though not directly comparing organic and conventionally grown grain, have reported grain protein levels in organic systems to be lower than is required for breadmaking[7,26,42].

The effect of organic management systems on other wheat quality parameters such as test weight, falling number and flour yield has been less frequently studied. Gooding et al.[7] reported that the test weights of several cultivars grown under organic management were adequate for breadmaking ($>75\,kg\,hl^{-1}$); thus test weight was not a significant constraint to marketing organic bread wheat. Storey et al.[42] also found test weights of organic wheat to be above $75\,kg\,hl^{-1}$. Baeckstrom et al.[37] and Poutala et al.[38] similarly reported that test weights were similar between organic and conventional cropping systems. Storey et al.[42] reported low Hagberg falling numbers for organically produced winter wheat, while Gooding et al.[7] found falling number values of organically grown UK wheat cultivars to be lower than required for breadmaking in many instances. Baeckstrom et al.[37] reported that Swedish winter wheat cultivars grown under conventional and organic management had similar falling number values. Conversely, Granstedt and Kjellenberg[40] reported higher falling number values for wheat grown in biodynamic systems and Poutala et al.[38] found that falling number values were generally higher under organic cropping systems. Baeckstrom et al.[37] reported that although conventional values for flour yield were slightly higher in conventional systems, differences were not significant.

The objective of this experiment was to determine if quality differences exist between organically and conventionally grown CWRS cultivars, in order to establish

Table 1. Soil properties of 0–10 cm depth soil samples taken at experimental sites at ERS, Edmonton, AB, Canada in the 2003 and 2004 growing seasons directly after seeding.

	ERS-conventional			ERS-organic		
Soil property[1,2]	**2003**	**2004**	**System average**	**2003**	**2004**	**System average**
N ($kg\,ha^{-1}$)	156	65	111	74	76	75
P ($kg\,ha^{-1}$)	89	37	63	>130	58	>94
K ($kg\,ha^{-1}$)	>1300	473	>887	410	570	490
PH	6.8	5.9	6.4	6.6	6.3	6.5
Organic matter (%)	10.1	11.2	10.7	9.9	10.3	10.1
Textural class	Clay	Clay		Clay	Clay	

[1] Available N determined using $CaCl_2$ extraction[58].
[2] Available P and K determined using a modified Kelowna extract[58].

whether high-quality CWRS wheat can be produced on organically managed land. We also wished to determine if any wheat cultivars exhibited different and potentially superior breadmaking potential in organically managed systems, as this would suggest the potential for breeding wheat cultivars especially suited to high quality organic wheat production.

Materials and Methods

Twenty-seven CWRS wheat cultivars representing 114 years of Canadian wheat breeding were grown under both conventional and organic management systems. Field trials were conducted in 2003 and 2004 at the Edmonton Research Station (ERS), Edmonton, AB, Canada (53° 34′N, 113° 31′W) on one organically managed field and one conventionally managed field, located less than 1 km apart. Soils were classified as Orthic Black Chernozemics, typical of central Alberta[43].

The experiment was designed as a randomized compete block with four replicates. All plots were seeded at a rate of 300 viable seeds m^{-2}, according to local recommended seeding rates[44]. In 2003, plot dimensions were 6 m × 0.9 m and consisted of four rows spaced approximately 23 cm apart. Plots were seeded using a four row, double disk drill (Fabro Enterprises Ltd, Swift Current, SK, Canada). In 2004, plot dimensions at ERS were 4 m × 1.38 m, consisting of six rows spaced approximately 23 cm apart. Plots were seeded using a six row, no-till double disk drill (Fabro Enterprises Ltd, Swift Current, SK, Canada). Seed used each year was increased the previous year at the ERS on conventionally managed land. Seeds were free of disease and therefore did not receive chemical seed treatment prior to seeding. The trials were not irrigated. All trials were planted in May and harvested in early to mid-September.

Conventional sites were managed according to local recommendations[44,45]. Fertilizers were applied following soil fertility testing in early spring. At the 2003 site, fertilizer ($90\,kg\,ha^{-1}$ N as 46-0-0 and $28\,kg\,ha^{-1}$ P as 8-24-24) was broadcast after seeding. At the 2004 site, fertilizer ($39\,kg\,ha^{-1}$ N as 46-0-0) was banded at a depth of 8.5 cm into the soil in the fall of 2003 and again in spring 2004 ($11\,kg\,ha^{-1}$ N as 46-0-0 and $6\,kg\,ha^{-1}$ P as 8-24-24) prior to seeding. Soil tests were conducted after seeding each year at each site (Table 1). All conventional fields were cultivated and harrowed prior to planting in spring and received recommended rates[45] of MCPA Amine 500 to control broadleaf weeds.

Organically managed sites did not receive any applications of chemical fertilizers or herbicides, and were managed in accordance with the guidelines of the Organic Crop Improvement Association International Certification Standards[46]. The organic sites were situated on a section of land at the ERS that was first designated to be organically managed (no chemical fertilizers or synthetic pesticides) in the spring of 2001. This land received its last application of chemical fertilizer ($67\,kg\,ha^{-1}$ N as 46-0-0 and $22\,kg\,ha^{-1}$ P as 8-24-24) in the fall of 2000. The land was subsequently seeded to winter triticale (*Triticale hexaploide* Lart.) which was harvested in fall 2001; triticale stubble was left on the field. Prior to the planting of experiments, the organic land was divided into sections which were subsequently managed with different crop rotations.

The 2003 organic site was planted to fall rye in the fall of 2001, which was mowed throughout the summer of 2002. The vegetative fall rye was disked under in the fall of 2002, just prior to an application of composted dairy manure at a rate of $60\,t\,ha^{-1}$. In the spring of 2003, the land was cultivated and harrowed just prior to seeding of the 2003 trial. The 2004 organic site was left to triticale stubble in the fall of 2001 and was seeded with berseem clover (*Trifolium alexandrinum* L.) in the spring of 2002. Extreme drought across the Canadian Prairies in the 2002 growing season caused the clover crop to fail and the land was seeded to fall rye in late summer of 2002. In the summer of 2003, the fall rye was harvested, and the soil was disked and treated with an application of composted dairy manure at a rate of $60\,t\,ha^{-1}$. In the spring of 2004, the land was cultivated and harrowed prior to planting. Weeds at both organic sites were manually removed at the 5–6 leaf crop stage in each year, and were subsequently left untouched.

Table 2. Precipitation and mean temperature data[1] for the 2003 and 2004 growing seasons at ERS, Edmonton, AB, Canada.

	Precipitation (mm)						Mean temperature (°C)				
Year	May	June	July	Aug.	Sept.	Total	May	June	July	Aug.	Sept.
2003	35	42	61	47	–	185	10	15	19	18	–
2004	44	22	225	36	40	367	9	15	17	15	10
Normal[2]	49	87	92	69	44	341	12	16	18	17	11

[1] Data collected by the University of Alberta, ERS.
[2] Data from Environment Canada[59].
–, Data not available.

Despite the absence of leguminous crops in the rotation, the chernozemic soils typical of north central Alberta have developed under Prairie grassland and are thereby relatively high in fertility and organic matter.

Disease assessments were conducted at all site-years, and very mild and sporadic incidences of powdery mildew (*Erysiphe graminis*) and stripe rust (*Puccinia striiformis*) were observed, with no apparent differences between sites or years. Because of the low and infrequent disease incidence, it was determined that no control measures were necessary.

Plots were harvested using a Wintersteiger plot combine following maturity. Grain yield was recorded on a dry weight basis. Harvested grain samples were dried at 60°C for approx. 24 h and weed seeds were removed using a 2 mm mesh sieve (Canadian Standard Sieve Series No. 10). Hectoliter weight (i.e., test weight) was determined from a one pint (473 ml) subsample of plot yield.

Five of the 27 cultivars were chosen for quality analysis, where quality parameters (including test weight) were selected based on their importance in meeting breadmaking quality objectives and their use in the Canadian wheat grading system[47,48]. The cultivars (Red Fife (released 1885), Marquis (released 1910), Thatcher (released 1935), Park (released 1963) and McKenzie (released 1997)) were chosen as representatives of some of the most important wheat cultivars in the history of CWRS wheat breeding. Grain samples from each replication of the 2003 and 2004 sites were analyzed for breadmaking quality traits at the Cereal Research Centre, Agriculture and Agri-Food Canada, Winnipeg. Grain samples (~20 g) used to determine wholemeal protein (PRO), PSI and wholemeal SDSS volume were ground using an UDY Cyclone Sample Mill (UDY Corporation, Fort Collins, CO, USA) using a 1.0 mm screen. Wholemeal protein (N × 5.7) and PSI were then determined using a 3 g flour sample in an Instalab 600 Series Near-Infrared Reflectance Analyzer (DICKEY-john Corporation, Auburn, IL, USA). SDSS tests were conducted in accordance with Approved Method 56–61A[49]. Flour Yield was determined using a Brabender Quadrumat Junior Mill (C.W. Brabender Instruments, South Hackensack, NJ, USA) according to the Approved Method 26–50[49]. Falling number tests were conducted according to Approved Method 56–81B[49]. All flour tests were expressed on a 14% moisture basis.

Mixograph parameters were determined using a 10 g fixed bowl mixograph (K&S Tool and Die Ltd, Winnipeg, MB, Canada) at 60% water absorption. Automated data collection and analysis were performed as described by Pon et al.[50]. Measurements included mixing development time (MDT), peak height, total energy under the graph, energy to peak (ETP), peak bandwidth (PBW) and bandwidth energy.

Analyses of data were performed using the PROC MIXED procedure of SAS[51]. The experiment was analyzed as a split plot, with management system as the main plot and cultivar as the subplot. Years were treated as blocks and were considered as a random effect in both combined analysis and analysis by management system. Cultivar and management system (where applicable) were considered as fixed effects. Effects were considered significant at $P \leqslant 0.10$, an appropriate level for an experiment of small size[52]. Data were also analyzed using a fixed effects model, with the PROC GLM procedure of SAS, for the purpose of exploring the percent variation attributable to year, cultivar, management and their interactions. Single degree of freedom contrasts were employed to identify differences in the breadmaking quality of cultivars in conventional versus organic systems. Pearson's coefficients of correlation were computed using genotypic least squares means within each management system (organic and conventional) within the PROC CORR procedure of SAS. Three of the six mixograph parameters, namely peak height, total energy under the graph and bandwidth energy, were found to be non-significant for all effects and are hereafter not discussed.

Results and Discussion

The organic and conventional sites were less than 1 km apart, with similar growing temperatures and precipitation levels within years (Table 2); thus differences between the two systems are likely due to the different management strategies and the resulting differences in nutrient levels (Table 1) and weed pressure. Weed biomass was significantly higher at the organic sites, with an average biomass of 134 g m^{-2} under organic management and 1.4 g m^{-2} under conventional management. The main effect of management was significant for grain yield, test weight, SDSS volume and mixograph PBW (Table 3). Management × cultivar interactions were significant for MDT,

Table 3. Least squares means and analyses of variance of grain yield, test weight, grain protein, wholemeal protein, flour yield (FLY), falling number (FN), PSI, SDSS, MDT, ETP and PBW for CWRS cultivars grown under conventional and organic management in Edmonton, AB, Canada in 2003 and 2004[1].

Cultivar	YOR[2]	Yield ($t\,ha^{-1}$)	Test weight ($kg\,hl^{-1}$)	Grain protein (%)	FLY (%)	FN	PSI (%)	SDSS (ml)	MDT (min)	ETP (%)	PBW (% torque min^{-1})
						Conventional					
Red Fife	1885	3.5	79	14.2	67	434	61	42.9	2.1	26	16
Marquis	1910	3.8	79	15.5	69	435	56	45.3	2.0	26	18
Thatcher	1935	3.7	78	15.3	70	500	56	43.9	2.2	33	18
Park	1963	4.0	78	14.9	70	500	55	42.3	2.3	37	18
McKenzie	1997	3.6	78	14.4	72	500	54	41.1	2.3	39	18
Conventional mean		3.7	78	14.9	70	474	56	43.1	2.2	32	17.6
$F\ test_{cultivar}$		ns	ns	**	**	ns	***	ns	ns	ns	ns
$SE_{cultivar}$		0.83	0.5	0.30	0.8	46.9	0.6	1.90	0.14	6.1	1.3
						Organic					
Red Fife	1885	2.5	73	14.1	67	471	60	37.6	1.7	19	19
Marquis	1910	3.0	77	15.1	69	464	55	41.0	2.2	33	19
Thatcher	1935	3.3	77	14.4	72	492	55	39.8	2.1	30	19
Park	1963	3.7	78	15.1	69	489	57	43.9	2.4	45	18
McKenzie	1997	3.3	78	14.6	69	495	54	41.5	2.4	46	19
Organic mean		3.2	77	14.7	69	482	56	40.8	2.2	35	19
$F\ test_{cultivar}$		*	ns	ns	ns	ns	*	ns	**	***	ns
$SE_{cultivar}$		0.30	3.1	0.69	1.9	19.4	1.4	2.19	0.14	5.1	1.1
						Combined ANOVA					
$F\ test_{mgmt}$		*	*	ns	ns	ns	ns	**	ns	ns	**
SE_{mgmt}		0.27	1.0	0.23	0.6	8.4	0.5	0.75	0.09	7.4	0.5
$F\ test_{cultivar}$		ns	ns	*	*	ns	***	ns	**	**	ns
$SE_{cultivar}$		0.43	1.5	0.37	1.0	33.1	0.8	1.74	0.10	4.2	0.8
$F\ test_{mgmt*cultivar}$		ns	ns	ns	ns	ns	ns	ns	**	ns	ns

[1] *F* values significant at the following levels: ***0.01, **0.05, *0.1. ns denotes non-significance.
[2] YOR indicates year of release.

while cultivar main effects were significant for several traits, including grain protein, flour yield, PSI, MDT and ETP (Table 3).

Grain yield was greater under conventional management, with average grain yields of $3.7\,t\,ha^{-1}$ compared to $3.2\,t\,ha^{-1}$ under organic management (Table 3). Test weight was lower on organic land ($77\,kg\,hl^{-1}$) compared to conventional ($78\,kg\,hl^{-1}$). It is likely that the elevated competition with weeds for moisture and nutrients on organic land contributed to lower grain yields and test weights. Many studies conducted on conventional land have reported similar results, where grain yields were reduced by the presence of weeds in the crop[27,53,54]; however the effect of weeds and the resulting competition for resources on test weight is less clearly defined. Das and Yaduraju[53] reported test weight of wheat was not significantly affected by weed growth and that frequent irrigation increased test weight. They also reported that the effect of chemical N, P and K fertilizers on test weight was significant yet erratic. While test weights in the present study did differ between the two systems, averages for each management system were above the minimum $75\,kg\,hl^{-1}$ for a No. 1 CWRS grading. In terms of cultivar averages, only Red Fife under organic management was below the desired level, with an average test weight of $73\,kg\,hl^{-1}$, meaning, all other factors remaining equal, that it would receive a No. 2 CWRS grading[48].

Mean wholemeal protein content did not differ between conventional and organic management systems (Table 3). This is supported by Shier et al.[18] and Ryan et al.[41], who reported no significant difference between grain protein content of organically and conventionally grown wheat, which Shier et al.[18] attributed to adequate soil N levels in both systems. Conversely, Baeckstrom et al.[37] and Poutala et al.[38] reported higher grain protein concentrations under conventional management than in organic cropping systems. Overall, protein contents were high under both conventional and organic management, at 14.9 and 14.7%, respectively. This level of protein content surpasses the minimum standard of 13.5% protein for CWRS wheat (Table 3), indicating the potential for growing high-quality bread wheat under either management system in north central Alberta. While varietal differences in protein were significant (Table 3), average protein content for all cultivars again exceeded 13.5% protein (data not shown). Marquis achieved the highest protein level, while Red Fife achieved the lowest.

Post-seeding soil tests in the current study indicated that in 2003, the conventional site had greater N levels than the organic site, while in 2004, the organic and conventional sites had similar N content (Table 1). Averaged across years, N content was 75 kg ha^{-1} in the organic system and 111 kg ha^{-1} in the conventional system. There are several possible explanations for the relatively high protein levels of the organically grown wheat in the current study, despite comparatively low-soil N concentrations. Crop residues and animal manure can increase soil biological activity, altering the extent and timing of nutrient availability[31–33]. This could be related to mycorrhizal colonization, which has been found to be greater in organic soils than in conventional soils[34]. Though these effects were not measured in the present study, the organically managed land did receive applications of composted manure and greater crop residues than the conventionally managed sites.

Crop stress (e.g., limited moisture) has been found to shorten the duration of starch deposition into the wheat kernels, thereby increasing the ratio of protein to starch, ultimately increasing protein percentage[25]. In the present experiment, it may be that crop weeds created some moisture stress and, despite lower N availability, helped to increase the ratio of protein to starch. Mason and Madin[27] reported that the effect of weeds on the protein content of wheat was variable across sites and suggested that the impact of weeds on wheat protein was likely dependent on late season competition between crop and weeds for nitrogen and water, and on the interaction between those factors. Another possible explanation for the relatively high protein content of organic wheat is that the soil analyses may not have adequately described the potential of the soil to supply nitrogen to the crop. Our soil analyses measured nitrate-nitrogen (NO_3), which varies with changes in soil temperature, moisture and biological activity[55]. Wallace[55] suggested that analyses of nitrate-nitrogen give an idea of the current, rather than long-term, N status of the soil.

Higher gluten strength, as measured by SDSS, occurred under conventional (43 ml) as opposed to organic (41 ml) management (Table 3). While no studies comparing the quality of organically and conventionally grown wheat have considered SDSS, Gooding et al.[8], Lloveras et al.[19] and Ames et al.[20] reported increases in SDSS volumes with nitrogen fertilization in UK bread wheat, Spanish bread wheat and Canadian durum wheat, respectively. Thus, higher SDSS volumes under conventional management in the current study could be due to higher N availability at conventional sites. Dexter et al.[21] suggested that increases in SDSS volumes from increases in N fertilizer were related to overall increases in protein. Ames et al.[20] reported a trend in durum wheat towards higher SDSS volumes with increasing protein. In the current study, SDSS volumes were not related to protein content on conventional land, but were positively associated with protein content on organic land (Table 4). These discrepancies suggest that a difference may exist in the partitioning of high- and low-molecular weight proteins between organically and conventionally grown wheat, which may be related to the stresses associated with organic production.

Average mixograph values for each management system revealed trends toward higher dough strength under organic management (Table 3). The main effect of management on PBW was significant, as was the management × cultivar interaction for MDT. PBW was higher on organic land than conventional, measuring 19 and 17.6% torque min^{-1}, respectively, reflective of stronger glutenic bonds that may be more tolerant to mixing. Examination of the management × cultivar interaction for MDT reveals that organically grown Red Fife performed poorly relative to all other cultivars in either management system, with an MDT of 1.7 min, indicating low dough strength. Conventional Red Fife, with an MDT of 2.1 min, performed equally or better than all but the organic Park and McKenzie, both at 2.4 min. This interaction suggests that it may be possible to select for high-quality wheat cultivars specific to organic environments.

In order to assess the effects of genotypic and environmental factors, we considered year, management system and their interaction as environmental effects, and as expected, cultivar effects in our model are discussed as genotypic effects. Environmental effects (year, management, year × management) accounted for over 35% of the variation in grain yield, test weight, wholemeal protein and PBW (Table 5). Fowler and De la Roche[15] reported that yield, test weight and protein exhibited the largest response to environment, while Preston et al.[16] similarly suggested that flour protein was most influenced by environment. The effect of year was more prominent than the effect of management system, which contributed less than 10% of the variation in all traits except for yield (14%) and SDSS volume (16%) (Table 5). Fowler and De la Roche[15] reported that SDSS volume was influenced equally by genotype and environment, and our results indicate a similar outcome for both SDSS and falling number. Of the three mixograph parameters measured, MDT and ETP were more influenced by genotype than by environment, representing the possibility for achieving high-breadmaking quality on organic land (Table 5). Fowler and De la Roche[15] reported that MDT showed a high degree of heritability compared to the influence of environment, although the effects of genotype and environment on other mixograph parameters in that study were less clearly defined. MDT has been reported to be strongly associated with farinograph dough development time and stability[56], and a study of CWRS wheat by Preston et al.[16] suggested that farinograph dough development time and stability were mainly influenced by genotype. Cultivar main effects accounted for less than 25% of the variation in four of the six remaining breadmaking quality traits; however cultivar effects were considerable for PSI (kernel hardness) and flour yield (Table 5). Fowler and De la Roche[15] reported a larger genetic influence than environmental for kernel hardness and flour yield, and Preston et al.[16] reported

Table 4. Genotypic correlations of yield, test weight, protein, PSI, flour yield, falling number (FN), SDSS and mixograph parameters[1] of five CWRS cultivars, released 1885–1997, grown at conventionally and organically managed sites in 2003 and 2004 at ERS, Edmonton, AB, Canada[2,3].

	Yield	Test weight	Protein	PSI	Flour yield	FN	SDSS	MDT	ETP	PBW
Yield		–	–	–	–	–	–	–	–	–
Test weight	0.90**		–	–	−0.80*	−0.99***	–	−0.91**	−0.92**	−0.80*
Protein	–	–		–	–	–	–	–	–	–
PSI	–	−0.83*	–		−0.93**		–	–	–	−0.96**
Flour yield	–	–	–	–		0.81**	–	–	0.88**	0.91**
FN	–	–	–	–	–		–	0.91**	0.93**	0.81*
SDSS	0.90**	0.86*	0.85*	–	–	–		−0.84*	–	–
MDT	0.88**	0.97***	–	–	–	–	0.92**		0.95**	–
ETP	0.87*	0.90**	–	–	–	–	0.92**	0.97***		–
PBW	–	–	−0.81*	–	–	–	–	–	–	

[1] Mixograph parameters include MDT, ETP and PBW.
[2] *r* values significant at the following levels: ***0.01, **0.05, *0.1. '_' denotes non-significance.
[3] Correlations above the diagonal represent conventional management, while those below the diagonal represent organic management.

Table 5. Percent sums of squares (using fixed effects analyses of variance) for the grain parameters yield, test weight, wholemeal protein, flour yield, falling number, PSI and SDSS and for the mixograph parameters MDT, ETP and PBW.

		Grain parameters							Mixograph parameters		
Effect	**df**	**Yield**	**Test weight**	**Wholemeal protein**	**Flour yield**	**Falling number**	**PSI**	**SDSS**	**MDT**	**ETP**	**PBW**
		(% Total sum of squares)									
Year	1	21	40	46	0	20	0	2	4	12	46
Management (Mgmt)	1	14	8	1	2	1	0	16	0	1	5
Year∗Mgmt	1	2	1	1	0	0	1	1	2	7	0
Cultivar	4	12	8	21	40	22	70	14	26	28	3
Year∗Cultivar	4	8	8	6	13	20	2	15	4	4	4
Mgmt∗Cultivar	4	3	9	6	15	5	3	22	10	5	4
Year∗Mgmt∗Cultivar	4	20	12	10	12	4	6	7	3	3	5
Error	60	19	15	9	18	29	18	23	50	42	33
Corrected total	79	100	100	100	100	100	100	100	100	100	100

Note: Corrected totals may not sum to 100% due to rounding.

genotype to be the main contributor to kernel hardness, although they reported the effect of environment to be significant as well.

Grain yield was positively associated with test weight, SDSS volume, MDT and ETP under organic management, but not under conventional management, suggesting that cultivars that yield well on organic land also possess higher breadmaking quality (Table 4). This may be related to varietal ability to withstand stresses associated with organic management, since the same relationships were not observed in the relatively low-stress conventional system. Test weight was found to be negatively associated with

flour yield, falling number, MDT, ETP and PBW on conventional land, while it was positively related to SDSS volume, MDT and ETP on organic land. If varieties that are capable of attaining high-grain yield and test weight under organic management are consistently found to have high-breadmaking quality, selection of high-quality wheat for organic production could be simplified.

Within the conventional management system, the main effect of cultivar was significant for wholemeal protein, flour yield and PSI (kernel hardness), with Red Fife among the lowest in protein and flour yield, with the softest kernels (Table 3). Under organic management, cultivars differed for grain yield, PSI, MDT and ETP, again with Red Fife having the lowest grain yield, MDT, ETP, and the softest kernels (Table 3). In both systems, Park and McKenzie were the superior cultivars, while Red Fife appeared to be the least suitable cultivar for breadmaking of the five cultivars tested, suggesting that older CWRS cultivars may not be suitable for breadmaking by today's conventional breadmaking standards. However Marquis and Thatcher, released in 1910 and 1935, respectively, had some of the highest protein contents under conventional management, while McKenzie, released in 1997, was among the lowest (yet adequate) in protein content. Further, Park was released in 1963 and could hardly be considered a 'modern' wheat cultivar. In a study of 14 CWRS cultivars released from 1981 to 1995, Preston et al.[16] reported no trends in quality parameters, including protein content, between registration date and cultivar. A study by Wang et al.[57] on the semi-arid Prairies indicated that Marquis had significantly lower protein content than newer cultivars released 1996–1999, primarily due to more efficient utilization of plant N, rather than increased N uptake by the newer cultivars. However, it is possible that this relationship may be altered by increased soil moisture levels.

There were few differences in the performance of individual cultivars in the two systems, excepting Red Fife. Red Fife was the oldest cultivar (released 1885), and it exhibited higher test weight, SDSS, MDT and ETP under conventional when compared to organic management (Table 3). The PBW of Red Fife was higher under organic management. In general, our results suggest that protein quality of Red Fife was higher under conventional management. Marquis (released in 1910) had lower MDT time under conventional management versus organic, reflecting higher breadmaking quality under organic management. The cultivar Thatcher (released in 1935) did not perform differently between the two management systems. Park (released in 1963) exhibited significantly higher SDSS volume under organic management, indicating higher breadmaking quality. McKenzie (released in 1997) produced higher flour yield under conventional management. The variability of the performance of these cultivars within the two systems allows us to conclude that older cultivars do not necessarily perform better on organic land in terms of breadmaking quality.

Conclusions

Grain yield and test weight were higher on conventional land when compared to organic; however protein content did not differ between the two systems, despite the probability that overall N availability was higher at the conventional sites. Despite existing differences between management systems and cultivars, test weight and protein content were sufficiently high in both management systems to meet the grading requirements for CWRS wheat. Gluten strength, as measured by SDSS volume, was improved under conventional management, possibly as a result of higher overall N availability. The trend towards enhanced dough strength of organically grown cultivars, as determined through the use of the mixograph, requires further examination. Overall, the results of this study suggest that organically managed CWRS wheat varieties are capable of achieving good breadmaking quality. The significant management × cultivar interaction for MDT indicates that some cultivars may be able to achieve higher breadmaking quality when grown on organic land than if grown on conventional land, and implies that breeding specifically for high-quality organic wheat production may be possible. Grain yield, test weight and protein content were largely determined by environment, while flour yield, kernel hardness, MDT and ETP were more influenced by genotypic factors. Falling number and SDSS volume were similarly influenced by genotype and environment. The cultivar Red Fife, released in 1885, had the poorest breadmaking quality of the five cultivars studied, while the most modern cultivars, Park and McKenzie, had the highest quality. This suggests that the oldest CWRS cultivars may not be suitable for breadmaking, regardless of management system. The variable performance of old and new cultivars under different management regimes indicated that older cultivars, while selected prior to the widespread use of pesticides and fertilizers in breeding programs, may not be better suited to organic production.

Acknowledgements. The technical assistance of Byron Cordero, Amy Kaut, Dione Litun, Dan Stanton and Klaus Strenzke is gratefully acknowledged. This research has been supported by the Canadian Wheat Board, the Organic Agriculture Centre of Canada (OACC), the Alberta Crop Industry Development Fund, the Alberta Agricultural Research Institute, check-off funds provided through the Western Grains Research Foundation and a Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant.

References

1 Cauvain, S.P. 2003. Wheat and its special properties. In X.P. Cauvain (ed.). Bread Making: Improving Quality. Woodhead Publishing Ltd, Cambridge, UK. p. 2–3.

2 Canadian Wheat Board (CWB). 2001. Grain matters: wheat report for the 1999–2000 crop year. Available at Web site http://www.cwb.ca/en/publications/farmers/jan-feb-2001/02-12-00-6.jsp (accessed November 2002).

3 Canadian Wheat Board (CWB). 2005. Canada Western Red Spring wheat — CWRS. Available at Web site http://www.cwb.ca/en/buying/high_quality/2005/no1cwrs (accessed July 2005).
4 Williams, P. 1997. Cultivar development and quality control of wheat in Canada. Paper presented at the International Japanese Conference on Near-Infrared Reflectance, 1997. Available at Web site http://collection.nlc-bnc.ca/100/200/301/cgc-ccg/cultivar_development-e/cultivar4-e.htm (accessed July 2005).
5 Ohm, J.B. and Chung, O.K. 1999. Gluten, pasting and mixograph parameters of hard winter wheat flours in relation to breadmaking. Cereal Chemistry 76:606–613.
6 Souza, E.J., Martin, J.M., Guttieri, M.J., O'Brien, K.M., Habernicht, D.K., Lanning, S.P., McLean, R., Carlson, G.R., and Talbert, L.E. 2004. Influence of genotype, environment, and nitrogen management on spring wheat quality. Crop Science 44:425–432.
7 Gooding, M.J., Cannon, N.D., Thompson, A.J., and Davies, W.P. 1999. Quality and value of organic grain from contrasting breadmaking wheat cultivars and near isogenic lines differing in dwarfing genes. Biological Agriculture and Horticulture 16:335–350.
8 Gooding, M.J., Davies, W.P., Thompson, A.J., and Smith, S.P. 1993. The challenge of achieving breadmaking quality in organic and low input wheat in the UK—A Review. Aspects of Applied Biology 36:189–198.
9 Peterson, C.J., Graybosch, R.A., Shelton, D.R., and Baenziger, P.S. 1998. Baking quality of hard winter wheat: response of cultivars to environment in the Great Plains. Euphytica 100:157–162.
10 Khatkar, B.S., Bell, A.E., and Scholfield, D. 1996. A comparative study of the inter-relationships between mixograph parameters and bread-making qualities of wheat flours and glutens. Journal of the Science of Food and Agriculture 72:71–85.
11 Fowler, D.B. and Kovacs, M.I.P. 2004. Influence of protein concentration on farinograph absorption, mixing requirement and mixing tolerance. Canadian Journal of Plant Science 84:765–772.
12 Johansson, E., Prieto-Linde, M.L., Svensson, G., and Jönsson, J.Ö. 2003. Influences of cultivar, cultivation year and fertilizer rate on amount of protein groups and amount and size distribution of mono- and polymeric proteins in wheat. Journal of Agricultural Science 140:275–284.
13 Lerner, S.E., Seghezzo, M.L., Molfese, E.R., Ponzio, N.R., Cogliatti, M., and Rogers, W.J. 2006. N- and S-fertiliser effects on grain composition, industrial quality and end-use in durum wheat. Journal of Cereal Science 44:2–11.
14 Rharrabti, Y., Royo, C., Villegas, D., Aparicio, N., and García del Moral, L.F. 2003. Durum wheat quality in Meditteranean environments. I. Quality expression under different zones, latitudes and water regimes across Spain. Field Crops Research 80:123–131.
15 Fowler, D.B. and De la Roche, I.A. 1975. Wheat quality evaluation. 3. Influence of genotype and environment. Canadian Journal of Plant Science 55:263–269.
16 Preston, K.R., Hucl, P., Townley-Smith, T.F., Dexter, J.E., Williams, P.C., and Stevenson, S.G. 2001. Effects of cultivar and environment on farinograph and Canadian short process mixing properties of Canada Western Red Spring wheat. Canadian Journal of Plant Science 81:391–398.
17 Randall, P.J., Freney, J.R., Smith, C.J., Moss, H.J., Wrigley, C.W., and Galbally, I.E. 1990. Effect of additions of nitrogen and sulfur to irrigated wheat at heading on grain yield, composition and milling and baking quality. Australian Journal of Experimental Agriculture 30:95–101.
18 Shier, N.W., Kelman, J., and Dunson, J.W. 1984. A comparison of crude protein, moisture, ash and crop yield between organic and conventionally grown wheat. Nutrition Reports International 30:71–76.
19 Lloveras, J., Lopez, A., Ferran, J., Espachs, S., and Solsona, J. 2001. Bread-making wheat and soil nitrate as affected by nitrogen fertilization in irrigated Mediterranean conditions. Agronomy Journal 93:1183–1190.
20 Ames, N.P., Clarke, J.M., Dexter, J.E., Woods, S.M., Selles, F., and Marchylo, B. 2003. Effects of nitrogen fertilizer on protein quantity and gluten strength parameters in durum wheat (*Triticum turgidum* L. var. *durum*) cultivars of variable gluten strength. Cereal Chemistry 80:203–211.
21 Dexter, J.E., Crowle, W.L., Matsuo, R.R., and Kosmolak, F.G. 1982. Effect of nitrogen fertilization of the quality characteristics of five North American amber durum wheat cultivars. Canadian Journal of Plant Science 62:901–912.
22 Guttieri, M.J., Ahmad, R., Stark, J., and Souza, E. 2000. End-use quality of six hard red spring wheat cultivars at different irrigation levels. Crop Science 40:631–635.
23 Kimball, B.A., Morris, C.F., Pinter, P.J. Jr, Wall, G.W., Hunsaker, D.J., Adamsen, F.J., LaMorte, R.L., Leavitt, S.W., Thompson, T.L., Matthias, A.D., and Brooks, T.J. 2001. Elevated CO_2, drought and soil nitrogen effects on wheat grain quality. New Phytologist 150:295–303.
24 Xu, Z.-Z. and Yu, Z.-W. 2006. Nitrogen metabolism in flag leaf and grain of wheat in response to irrigation regimes. Journal of Plant Nutrition and Soil Science 169:118–126.
25 Jenner, C.F., Ugalde, T.D., and Aspinall, D. 1991. The physiology of starch and protein deposition in the endosperm of wheat. Australian Journal of Plant Physiology 18:211–226.
26 Nass, H.G., Ivany, J.A., and MacLeod, J.A. 2003. Agronomic performance and quality of spring wheat and soybean cultivars under organic culture. American Journal of Alternative Agriculture 18:164–170.
27 Mason, M.G. and Madin, R.W. 1996. Effect of weeds and nitrogen fertilizer on yield and grain protein concentration of wheat. Australian Journal of Experimental Agriculture 36:443–450.
28 Bavec, M., Bavec, F., Varga, B., and Kovačević, V. 2002. Relationships among yield, its quality and yield components in winter wheat (*Triticum aestivum* L.) cultivars affected by seeding rates. Die Bodenkultur 53:143–151.
29 Geleta, B., Atak, M., Baenziger, P.S., Nelson, L.A., Baltenesperger, D.D., Eskridge, K.M., Shipman, M.J., and Shelton, D.R. 2002. Seeding rate and genotype effect on agronomic performance and end-use quality of winter wheat. Crop Science 42:827–832.
30 Gooding, M.J., Pinyosinwat, A., and Ellis, R.H. 2002. Responses of wheat grain yield and quality to seed rate. Journal of Agricultural Science 138:317–331.
31 Burger, M. and Jackson, L.E. 2003. Microbial immobilization of ammonium and nitrate in relation to ammonification and nitrification rates in organic and conventional cropping systems. Soil Biology and Biochemistry 35:29–36.

32 Carpenter-Boggs, L., Kennedy, A.C., and Reganold, J.P. 2000. Organic and biodynamic management: effects on soil biology. Soil Science Society of America Journal 64:1651–1659.

33 Emmerling, C., Udelhoven, T., and Schroder, D. 2001. Response of soil microbial biomass and activity to agricultural de-intensification over a 10 year period. Soil Biology and Biochemistry 33:2105–2114.

34 Mader, P., Edenhofer, S., Boller, T., Wiemken, A., and Niggli, U. 2000. Arbuscular mycorrhizae in a long-term field trial comparing low-input (organic, biological) and high-input (conventional) farming systems in a crop rotation. Biology and Fertility of Soils 31:150–156.

35 Hawkins, H.-J., Johansen, A., and George, E. 2000. Uptake and transport of organic and inorganic nitrogen by arbuscular mycorrhizal fungi. Plant and Soil 226:275–285.

36 Singh, S. and Kapoor, K.K. 1999. Inoculation with phosphate-solubilizing microorganisms and a vesicular-arbuscular mycorrhizal fungus improves dry matter yield and nutrient uptake by wheat grown in a sandy soil. Biology and Fertility of Soils 28:139–144.

37 Baeckstrom, G.L., Hanell, U., and Svensson, G. 2004. Baking quality of winter wheat grown in different cultivating systems, 1992–2001: a holistic approach. Journal of Sustainable Agriculture 24:53–79.

38 Poutala, R.T., Korva, J., and Varis, E. 1993. Spring wheat cultivar performance in ecological and conventional cropping systems. Journal of Sustainable Agriculture 3:63–83.

39 Starling, W. and Richards, M.C. 1993. Quality of commercial samples of organically grown wheat. Aspects of Applied Biology 36:205–209.

40 Granstedt, A. and Kjellenberg, L. 1997. Long-term field experiment in Sweden: effects of organic and inorganic fertilizers on soil fertility and crop quality. In Agricultural Production and Nutrition, Proceedings of an International Conference, Boston, Massachusetts, 19–21 March 1997. p. 79–90. Available on Web site http://www.jdb.se/sbfi/publ/boston/boston7.html (accessed July 2005).

41 Ryan, M.H., Derrick, J.W., and Dann, P.R. 2004. Grain mineral concentrations and yield of wheat grown under organic and conventional management. Journal of the Science of Food and Agriculture 84:207–216.

42 Storey, T., Hogan, R., and Humphreys, J. 1993. The growth, yield and quality of winter wheat and winter oats grown under an organic conversion regime. Aspects of Applied Biology 36:199–204.

43 Alberta Agriculture, Food and Rural Development (AAFRD). 2004. Soil Group Map of Alberta. Available at Web site http://www.agric.gov.ab.ca/soils/soils.nsf/soilgroup-map?readform (accessed July 2005).

44 Alberta Agriculture, Food and Rural Development (AAFRD). 2005. Using 1000 kernel weight for calculating seeding rates and harvest losses. Available at Web site http://www.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex81/$file/100_22-1pdf?OpenElement (accessed July 2006).

45 Alberta Agriculture, Food and Rural Development (AAFRD). 2006. Herbicide selector. Available at Web site http://www.agric.gov.ab.ca/app23/herbsel (accessed July 2006).

46 Organic Crop Improvement Association (OCIA) International, Inc. 2000. International Certification Standards as Revised: March 2000. OCIA International, Inc., Lincoln, NE.

47 Canadian Grain Commission. 2006. Crop quality data, highlights and reports: Canadian Western wheat. Available at Web site http://www.grainscanada.gc.ca/Quality/Wheat/cdn-whtmenu-e.htm (accessed July 2006).

48 Anonymous. 2004. Official Grain Grading Guide. Canadian Grain Commission, Winnipeg, MB, Canada (verified 1 August 2004).

49 American Association of Cereal Chemists. 2000. Approved Methods of the AACC 10th ed. Methods 26–50, 56–61A, 56–81B. The Association, St. Paul, MN.

50 Pon, C.R., Lukow, O.M., and Buckley, D.J. 1989. A multi-channel, computer-based system for analyzing dough rheology. Journal of Texture Studies 19:343–360.

51 SAS Institute. 1999. Release 8.2. SAS Institute, Inc., Cary, NC.

52 Steel, R.G.D., Torrie, J.H., and Dickey, D.A. 1997. Principles and Procedures of Statistics: A Biometrical Approach, 3rd ed. McGraw-Hill, New York.

53 Das, T.K. and Yaduraju, N.T. 1999. Effect of weed competition on growth, nutrient uptake and yield of wheat as affected by irrigation and fertilizers. Journal of Agricultural Science 133:45–51.

54 Thompson, G.B. and Woodward, F.I. 1994. Some influences of CO_2 enrichment, nitrogen nutrition and competition on grain yield and quality in spring wheat and barley. Journal of Experimental Botany 45:937–942.

55 Wallace, J. (ed.) 2001. Organic Field Crop Handbook, 2nd ed. Canadian Organic Growers, Ottawa, ON, Canada.

56 Kaur, K., Lukow, O.M., Preston, K.R., and Malcolmson, L.J. 2004. How well do early-generation quality tests predict flour performance? Canadian Journal of Plant Science 84:71–78.

57 Wang, H., McCaig, T.N., DePauw, R.M., Clarke, F.R., and Clarke, J.M. 2002. Physiological characteristics of recent Canada Western Red Spring wheat cultivars: yield components and dry matter production. Canadian Journal of Plant Science 82:299–306.

58 Norwest Labs. 2003. Agricultural schedule of services. Available at Web site http://www.norwestlabs.com/what_we_do/agrisos20032004noprices.pdf (accessed July 2006).

59 Environment Canada. 2004. Canadian climate normals 1971–2000. Edmonton City Centre. Available at Web site http://www.climate.weatheroffice.ec.gc.ca/climate_normals/results_e.html (accessed January 2005).

Renewable Agriculture and Food Systems: 22(3); 168–180 doi:10.1017/S1742170507001706

Crop and cattle responses to tillage systems for integrated crop–livestock production in the Southern Piedmont, USA

A.J. Franzluebbers*, and J.A. Stuedemann

USDA–Agricultural Research Service, 1420 Experiment Station Road, Watkinsville, GA 30677, USA.
*Corresponding author: afranz@uga.edu

Accepted 11 September 2006 **Research Paper**

Abstract

Integration of crops and livestock has the potential to provide a multitude of benefits to soil and water conservation and nutrient cycling efficiency, while reducing economic risk and increasing profitability. We conducted a field study from May 2002 to October 2005 to determine crop and cattle responses to three management factors on a Typic Kanhapludult in Georgia, USA. Summer grain/winter cover [sorghum (*Sorghum bicolor* L. Moench) or corn (*Zea mays* L.)/rye (*Secale cereale* L.)] and winter grain/summer cover [wheat (*Triticum aestivum* L.)/pearl millet (*Pennisetum glaucum* L. R. Br.)] were managed with either conventional tillage (CT) or no tillage (NT) and with or without cattle grazing of cover crops. All crops were successfully established, irrespective of tillage and cover crop management. Although pearl millet was often lower in the plant stand with NT than with CT, plants compensated with greater biomass on an area basis. Across years, grain yield of sorghum (1.9 Mg ha^{-1} during three seasons) and corn (7.3 Mg ha^{-1} in one season) was 25% greater under NT than under CT when the cover crop was not grazed. Wheat grain yield (2.7 Mg ha^{-1} during three seasons) was unaffected by tillage and cover crop management. Unharvested stover production of summer grain crops was greater with NT than with CT (6.5 versus 4.1 Mg ha^{-1}; $P < 0.001$). Grazing rye rather than allowing it to accumulate as surface residue reduced summer grain yield 23% and reduced standing grain-crop dry matter 26% under NT, but had no effect under CT. In contrast, grazing pearl millet rather than allowing it to accumulate as surface residue increased wheat standing dry matter yield by 25 ± 14% (mean ± standard deviation among 3 years and two tillage systems). Ungrazed cover crop production was greater under NT than under CT for rye (7.0 versus 6.0 Mg ha^{-1}; $P = 0.03$) and pearl millet (10.2 versus 7.6 Mg ha^{-1}; $P = 0.01$). Calf daily gain was either greater or tended to be greater under NT than under CT on rye (2.27 versus 2.09 kg head^{-1} d^{-1}; $P = 0.15$) and pearl millet (2.05 versus 1.81 kg head^{-1} d^{-1}; $P = 0.05$). Total cattle gain per grazing season was either greater or tended to be greater with NT than with CT on rye (350 versus 204 kg ha^{-1}; $P = 0.01$) and pearl millet (324 versus 277 kg ha^{-1}; $P = 0.15$). Net return over variable costs was greater with grazing than without grazing of cover crops (US$302 versus −US$63 ha^{-1}; $P < 0.001$). Livestock grazing of cover crops had variable effects on subsequent crop production, but increased economic return and diversity overall. Therefore, an integrated crop–livestock production system with conservation tillage is recommended as a viable option for producers to diversify farming operations to avoid risk, improve ecological production of crops, and potentially avoid environmental damage from soil erosion and nutrient loss.

Key words: cattle production, conservation tillage, corn, cover cropping, pearl millet, rye, sorghum, wheat

Introduction

Integrated crop–livestock production is not common in modern agricultural production systems for a number of reasons. Technological advances in plant genetics, machinery and synthetic chemicals, as well as shifting government policies during the past century are the primary reasons that agriculture has been transformed from small, diversified farming operations to large specialized production

The use of trade, firm, or corporation names in this manuscript is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the USDA or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

© 2007 Cambridge University Press

facilities. Despite this change, a growing awareness is emerging that the stability and resiliency of modern agricultural landscapes are now becoming impaired by this shift to enterprise specialization, concentration of operations, and expansion of scale. Energy and nutrient cycles are becoming spatially and temporally compartmentalized in a manner far removed from natural ecosystem cycling[1]. There is a need to rediscover the mechanisms and attributes of integrated crop–livestock production systems to (1) enable more efficient utilization of natural resources (sunlight, water, biologically fixed N, and recycled nutrients), (2) exploit natural pest control phenomena, (3) reduce nutrient concentration and consequent environmental risk, and (4) improve soil functioning and productivity[2].

Soil organic matter is a critical component in maintaining soil quality[3]. Pastures are known to increase soil organic matter quantity due to large input of residues and lack of disturbance[4], which could lead to retention of organically bound nutrients and improved water relations in soil. Cropping systems under conditions of high soil organic matter have not been evaluated in the Southern Piedmont, USA, because much of the cropland has been degraded by historical cropping that caused excessive soil erosion[5]. Crop responses to tillage management following pasture termination may be significantly different than responses on previously degraded land, because of the presence of a large storage of nutrients, soil biological potential and improved soil physical structure.

Yield of crops as affected by tillage management in the southeastern USA has been investigated previously in several studies. A general recommendation has been hampered by the diversity of yield responses to tillage obtained. Yield reduction with NT compared with CT has been observed for sorghum in Texas[6], wheat stover in Texas[6], and wheat grain in North Carolina[7] and South Carolina[8]. Equivalent yield between conventional tillage (CT) and no tillage (NT) has been observed for wheat grain in Texas[6] and South Carolina[9]. Yield enhancement with NT compared with CT has been observed for sorghum in Georgia[10], for corn in North Carolina[11], Georgia[12], and Alabama[13], and for wheat in South Carolina (when preceded by deep ripping)[11]. The diversity of yield responses to tillage suggests that any NT advantage would be more likely to occur with summer grain crops than with winter grain crops.

The effect of tillage system on cover crop production has been previously investigated to a limited extent. On a Typic Rhodudult in Georgia, rye cover crop production was 5.9 Mg ha^{-1} under CT and 8.5 Mg ha^{-1} under NT during 2 years[14]. However, crimson clover (*Trifolium incarnatum* L.) cover crop production was lower under NT (3.6 Mg ha^{-1}) than under CT (5.7 Mg ha^{-1}). On a Plinthic Paleudult in Georgia, hairy vetch (*Vicia villosa* Roth.) cover crop production was 4.6 Mg ha^{-1} under moldboard plowing and 4.8 Mg ha^{-1} under NT during 2 years[15]. In this same study, winter annual weed production without a planted cover crop was 1.8 Mg ha^{-1} under moldboard plowing and 1.3 Mg ha^{-1} under NT. Cover crops have typically been incorporated into contemporary cropping systems only in combination with conservation tillage to obtain surface residue accumulation[16].

Climatic conditions in the Southern Piedmont are characterized by excessive precipitation to potential evapotranspiration during the winter growing season, but during the summer growing season precipitation is similar to potential evapotranspiration. The impact of time of grain cropping (i.e., winter versus summer) on grain yield and forage availability has not been directly evaluated, especially under conditions of initially high soil organic matter. Under a double-cropping environment in the southeastern USA, a cover crop following grain cropping could provide high-quality forage to supplement shortages from potential perennial pasture.

Animals grazing cover crops could compact soil due to excessive animal traffic, especially when the soil is wet. Tollner et al.[17] observed compaction from cattle traffic in a Southern Piedmont soil with low soil organic matter. However, surface residue cover may provide a significant buffer against animal trampling effects, such that NT crop production following long-term pasture could alleviate the negative effects of animal trampling.

We hypothesized that winter grain production would be more reliable than summer grain production due to milder temperature and less risk from drought. It is possible that time of grain production could interact with tillage management, such that NT might have a positive impact on summer grain production, but a negative impact on winter grain production due to lower temperature and excessive soil moisture. It is also more likely that winter grazing of a cover crop could compact soil compared with summer grazing, especially under CT. We conducted this study to assist crop and animal producers in determining the appropriate timing for grazing and tillage management to optimize crop production without degrading soil and water resources.

Materials and Methods

The experiment was located at the US Department of Agriculture (USDA)-Agricultural Research Service J. Phil Campbell Sr. Natural Resource Conservation Center in Watkinsville, GA (33° 62′ N, 83° 25′ W) on Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult). Soil was moderately acidic (pH~6) and contained moderate total N (1.2 g kg^{-1}) in the upper 20 cm. The experimental design was a completely randomized arrangement of 16 main plots. Main plots were a factorial arrangement of (a) tillage and (b) time of grain/cover cropping, which were replicated four times. Main plots were split into grazed (0.5 ha) and ungrazed (0.2 ha) cover crop treatments. A total of 16 main plots and 32 split plots were evaluated from May 2002 to October 2005.

Previously, the experimental area was in tall fescue [*Lolium arundinaceum* (Schreb.) S.J. Darbyshire] for 20

years. Unfertilized pasture growth during the three years just prior to the experiment was expected to remove differences in residual inorganic soil N among paddocks. All paddocks received dolomitic limestone (2.2 Mg ha^{-1}) immediately prior to termination of the tall fescue. The 16 experimental paddocks were regarded as an excellent starting point for the proposed research, because soil organic matter was at a high level[18] and grazing infrastructure was mostly in place at the site (fencing, gates, shades, mineral feeders, watering troughs, and animal handling facility).

Tillage systems were: (1) conventional disk tillage (CT) following harvest of each grain and cover crop and (2) NT with glyphosate to control weeds prior to planting. Tillage treatments were initiated in May 2002. Initial CT treatment consisted of moldboard plowing to a depth of 25–30 cm. Disk plowing only to a depth of 15–20 cm occurred in subsequent years. Pasture was terminated in the NT treatment with two applications of glyphosate (Table 1).

Cropping systems were: (1) winter grain cropping [wheat (*Triticum aestivum* L.); November planting and May/June harvest] with summer cover cropping {pearl millet [*Pennisetum glaucum* (L.) R. Br.]; June/July planting and September/October termination} and (2) summer grain cropping {grain sorghum [*Sorghum bicolor* (L.) Moench] or corn (*Zea mays* L.); April to June planting and September/October harvest} with winter cover cropping [cereal rye (*Secale cereale* L.); November planting and May termination]. Management details of each crop are reported in Table 1. Sorghum, rye, wheat, and pearl millet were planted with a John Deere grain drill for CT and a Great Plains drill for NT.

Cover crop management was: (1) no grazing and (2) grazing with cattle to consume 90% of available forage produced. Cover crops were stocked with yearling Angus steers in the summer of 2002 and in the spring of 2003 (Table 1). Thereafter, cow/calf pairs were used to simulate a more typical regional management approach. Stocking rates and weights are reported in Table 2. Ungrazed cover crops were grown until approx. 2 weeks prior to planting of the next crop and either (1) mowed prior to CT operations or (2) mechanically rolled to the ground in the NT system[19].

Application of N was relatively low during the first 3 years, but was adequate to assure early plant growth and development with further growth dependent upon the mineralization of stored nutrients in soil organic matter. Extractable P and K concentrations in the surface 7.5 cm of soil were $\geqslant$100 mg P kg^{-1} soil and 400 mg K kg^{-1} soil[20]; levels considered adequate for crop production.

Early-season plant population of crops was determined by counting the number of plants in two adjacent rows 1 m long at three locations in ungrazed plots and five locations in grazed plots. Plant populations were not determined during the first year of this study.

Grain yield was determined by weighing the contents of the entire experimental unit harvested with a field combine followed by unloading onto a truck with scales placed under all tires. A subsample of grain was collected for moisture determination and protein concentration (calculated as 6.25 × N concentration). Grain yield was adjusted to an oven-dried basis (55°C, $\geqslant$72 h). Standing grain-crop dry matter following grain harvest was determined from 0.15 × 1-m areas (three areas in ungrazed plots and five areas in grazed plots). Cover-crop above-ground dry matter was collected in the same manner. Hand-harvested yield was determined for wheat in 2004 from 0.38-m^2 areas, for sorghum in 2004 from 0.76-m^2 areas, and for corn in 2005 from 4.56-m^2 areas in each plot and separated into grain and stover components. Grain, stover and forage components were weighed before and after oven drying (55°C).

A variable stocking rate was used to consume $\geqslant$90% of available forage from each paddock. Stocking was targeted so that grazing could last for at least a month. Since grazing was initiated when cover crops were 0.3–0.5 m tall and actively growing, stocking estimates from experienced animal scientists were used rather than quantitative measures. Performance and production were determined from periodic weighing of cattle (2.4 ± 1.4 times per grazing season with 20 ± 11 days in each period). Cattle shrunk weight during each handling event was determined by not offering water for 16 h (evening prior to next day handling), herding animals into the nearby handling facility in the morning, and weighing of animals on a balance under a cattle chute. Cattle gain ha^{-1} was calculated as the difference in initial and final weight of all cattle placed on a paddock during a grazing season. Average daily gain was calculated from total weight gain divided by the number of cattle and grazing days in a season.

The general linear model procedure of SAS was used to analyze variances for each of the plant and animal responses during each growing season separately[21]. Means across years were analyzed for variance, with year as a random variable in the error term. Significant differences among means were declared at $P \leqslant 0.05$, unless otherwise indicated. Only a priori contrasts between cover crop treatments within a tillage system and between tillage systems with a cover crop management were considered.

Results and Discussion

Crop establishment

Establishment of most crops was not affected by tillage and cover crop management, except for pearl millet, corn and wheat (Table 3). Pearl millet population under NT was 66 ± 9% of that under CT during the 3 years of evaluation. One reason for the lower plant population with NT compared with CT may have been due to poorer seed-to-soil contact in the surface residue layer as a result of the need for shallow planting of the small seed. Also, occasional flocks of birds may have consumed seeds or seedlings when foraging in the residue-rich surface soil

Table 1. Crop management inputs and characteristics from 2002 to 2005 at Watkinsville GA.

	Summer grain/winter cover		Summer cover/winter grain	
Property	**Sorghum or corn**	**Rye**	**Pearl millet**	**Wheat**
Cultivar	*Sorghum*—Pioneer 83G66 (2002–2004) *Corn*—Pioneer 31N26 (2005)	Hi-Gainer (2002–2003), Wrens Abruzzi (2004)	Tifleaf 3 (2002–2005)	Crawford (2002), 518W (2003), Coker 9863 (2004)
Row spacing	*Sorghum*—34 cm (CT), 38 cm (NT) *Corn*—76 cm	19 cm	17 cm (CT), 19 cm (NT)	19 cm
Planting date	13–14 Jun 2002, 2–5 Jun 2003, 18–19 May 2004, 11 Apr 2005 (NT), 19 Apr 2005 (CT)	2 Dec 2002, 5 Nov 2003, 10–16 Nov 2004	12 Jun 2002, 26 Jun 2003, 22–23 Jun 2004, 6 Jul 2005 (NT), 28 Jul 2005 (CT)	28 Nov 2002, 4–6 Nov 2003, 10–16 Nov 2004
Harvest/ termination date	15–22 Nov 2002, 17–20 Oct 2003, 5–6 Oct 2004, 26 Sep–3 Oct 2005	7–12 May 2003, 27–28 Apr 2004, 6 Apr 2005	15–25 Nov 2002, 29 Sep 2003, 24–30 Sep 2004, 17–18 Oct 2005	11–19 Jun 2003, 3–4 Jun 2004, 17–20 Jun 2005
Fertilizer applications	*Limestone*—19 Mar 2002 (2.24 Mg ha^{-1}) NH_4NO_3—18 Jun 2002 (146 kg ha^{-1}), 12 Jun 2003 (150 kg ha^{-1}), 18 Jun 2004 (142 kg ha^{-1}), 24 May 2005 (325 kg ha^{-1}) *18-9-18(N-P_2O_5-K_2O)*—15–18 Apr 2005 (292 kg ha^{-1})	NH_4NO_3—25 Feb 2003 (153 kg ha^{-1}), 20 Feb 2004 (118 kg ha^{-1}), 3 Mar 2005 (147 kg ha^{-1})	*Limestone—19* Mar 2002 (2.24 Mg ha^{-1}) NH_4NO_3—18 Jun 2002 (146 kg ha^{-1}), 9 Jul 2003 (132 kg ha^{-1}), 19 Jul 2004 (148 kg ha^{-1}), 17 Aug 2005 (165 kg ha^{-1})	NH_4NO_3—25 Feb 2003 (153 kg ha^{-1}), 20 Feb 2004 (118 kg ha^{-1}), 3 Mar 2005 (147 kg ha^{-1})
Herbicide applications	*Glyphosate*—9 May 2002—NT (5.8 l ha^{-1}), 14 Jun 2002—NT (2.3 l ha^{-1}), 2–6 Jun 2003—NT (1.6 l ha^{-1}), 21 May 2004—NT (2.3 l ha^{-1}), 12 Apr 2005—NT (3.5 l ha^{-1}), 19 May 2005—NT (1.6 l ha^{-1}) *Atrazine*—2–6 Jun 2003 (4.7 l ha^{-1}), 6 Jun 2004 (4.7 l ha^{-1}) *Dual*—2–6 Jun 2003 (1.2 l ha^{-1})	*Glyphosate*—2 Dec 2002—NT (2.3 l ha^{-1}), 6 Nov 2003—NT (2.3 l ha^{-1}), 17 Nov 2004—NT (2.3 l ha^{-1})	*Glyphosate*—9 May 2002—NT (5.8 l ha^{-1}), 14 Jun 2002—NT (2.3 l ha^{-1}), 27 Jun 2003—NT (3.5 l ha^{-1})	*Glyphosate*—2 Dec 2002—NT (2.3 l ha^{-1}), 6 Nov 2003—NT (2.3 l ha^{-1}), 17 Nov 2004—NT (2.3 l ha^{-1}) *2,4-D amine*—23 Feb 2004 (2.3 l ha^{-1})
Initial cattle stocking date	13 Oct 2005	25 Mar 2003, 9 Mar 2004, 10 Mar 2005	11 Jul 2002, 6 Aug 2003, 2 Aug 2004, 23 Aug 2005	None
Termination cattle stocking date	27 Oct 2005	6 May 2003, 27 Apr 2004, 5 Apr 2005	26 Sep 2002, 1 Oct 2003, 21 Sep 2004, 4 Oct 2005	None

CT is conventional tillage and NT is no tillage.

Table 2. Cattle stocking characteristics averaged across the entire grazing period in two cropping systems managed with CT and NT.

	Summer grain/winter cover crop				Winter grain/summer cover crop				
Tillage	**2003**	**2004**	**2005**	**Mean**	**2002**	**2003**	**2004**	**2005**	**Mean**
Calf stocking rate (head ha^{-1})									
CT	6.0	3.1	4.4	4.5	6.7	3.3	4.0	4.0	4.5
NT	6.0	5.5	4.6	5.4	5.9	3.4	4.0	4.0	4.3
$LSD_{(P=0.05)}$	NV	2.7	0.9	0.8*	0.7*	0.3	NV	NV	0.2*
Calf head weight (kg head^{-1})									
CT	290	85	69	148	294	182	224	187	222
NT	292	92	73	152	306	206	214	196	231
$LSD_{(P=0.05)}$	14	20	19	9	8*	17*	24	26	8*
Cow head weight (kg head^{-1})									
CT	–	513	525	519	–	508	497	496	500
NT	–	552	490	521	–	513	536	520	523
$LSD_{(P=0.05)}$	–	52	49	32	–	74	52	49	29
Paddock stocking weight (Mg ha^{-1})									
CT	1.74	1.88	2.62	2.08	1.98	2.28	2.89	2.73	2.47
NT	1.75	3.57	2.60	2.64	1.81	2.46	3.00	2.86	2.53
$LSD_{(P=0.05)}$	0.09	1.94	0.68	0.59	0.21	0.44	0.15	0.28	0.12
Days of grazing (days)									
CT	42	49	26	39	77	57	50	31	54
NT	42	49	26	39	77	57	50	41	56
$LSD_{(P=0.05)}$	NV	NV	NV	NV	NV	NV	NV	3*	1*
Animal grazing days [(head d) ha^{-1}]									
CT	252	301	228	260	518	375	400	250	386
NT	252	539	240	344	455	390	400	330	394
$LSD_{(P=0.05)}$	NV	268	45	78*	55*	36	NV	21*	15

NV is no variance.
* Next to LSD value indicates significance between tillage means.

Table 3. Early-season population (plants m^{-2}) of grain and cover crops in two cropping systems varying in tillage system (CT and NT) and cover crop management (with and without cattle grazing).

		Summer grain/winter cover crop				Winter grain/summer cover crop			
Tillage	**Cover crop**	**2003**	**2004**	**2005**	**Mean**	**2003**	**2004**	**2005**	**Mean**
Grain crop		----------Sorghum or corn----------				----------Wheat----------			
CT	Ungrazed	29.6	18.0	5.9	17.8	159	60	–	110
	Grazed	29.3	22.1	6.2	19.2	141	68	–	105
NT	Ungrazed	26.0	13.9	7.2	15.7	136	70	–	103
	Grazed	29.5	15.9	7.7	17.7	180	79	–	129
$LSD_{(P=0.05)}$		5.8	5.1*	1.2*	2.4	18*	26	–	15*
Cover crop		----------Rye----------				----------Pearl millet----------			
CT	Ungrazed	146	135	–	141	124	130	102	118
	Grazed	143	141	–	142	125	108	94	109
NT	Ungrazed	150	134	–	142	71	82	77	77
	Grazed	160	143	–	152	68	75	69	70
$LSD_{(P=0.05)}$		30	34	–	22	37*	39*	19*	18*

Populations were determined for sorghum on 28 June 2003 and 18 June 2004, for corn on 29 April 2005, for wheat and rye on 12 December 2003 and 8 February 2005, and for pearl millet on 14 July 2003, 8 July 2004 and 16 August 2005.
A priori mean comparisons are between tillage systems within a cover crop management or between cover crop management within a tillage system. *Next to LSD value indicates significance in at least one of these comparisons.

Table 4. Grain yield, standing grain-crop dry matter, and cover-crop dry matter ($Mg\,ha^{-1}$) in two cropping systems varying in tillage system (CT and NT) and cover crop management (with and without cattle grazing).

		Summer grain/winter cover crop					Winter grain/summer cover crop				
Tillage	**Cover crop**	**2002**	**2003**	**2004**	**2005**	**Mean**	**2002**	**2003**	**2004**	**2005**	**Mean**
Grain yield		--------Sorghum (2002–2004) or corn (2005) --------					----------Wheat----------				
CT	Ungrazed	1.23	4.14	0.46	6.43	3.06	–	2.75	2.62	2.71	2.69
	Grazed	1.48	3.73	0.55	7.46	3.30	–	2.63	3.03	2.67	2.78
NT	Ungrazed	0.83	4.71	1.20	8.63	3.84	–	2.78	2.07	2.85	2.57
	Grazed	0.69	3.77	0.59	6.74	2.95	–	2.65	2.58	2.66	2.63
$LSD_{(P=0.05)}$		0.67*	1.38	0.33*	2.38	0.66*	–	0.51	0.59	1.05	0.41
Grain-crop standing dry matter		--------Sorghum (2002–2004) or corn (2005) --------					----------Wheat----------				
CT	Ungrazed	1.89	3.55	4.25	7.24	4.23	–	1.29	0.77	1.28	1.11
	Grazed	1.77	2.84	4.13	7.50	4.06	–	1.41	1.09	1.78	1.43
NT	Ungrazed	2.17	7.31	8.40	11.92	7.45	–	1.47	1.02	1.39	1.29
	Grazed	2.27	5.05	6.50	8.29	5.53	–	1.60	1.24	1.82	1.55
$LSD_{(P=0.05)}$		1.33	1.29*	2.32*	3.97*	1.13*	–	–	0.37	0.42*	0.21*
Cover-crop standing dry matter		----------Rye----------					----------Pearl millet----------				
CT	Ungrazed	–	7.21	6.67	4.21	6.03	5.28	7.29	8.72	9.09	7.59
	Grazed	–	0.62	0.18	0.02	0.27	0.40	0.38	0.36	0.58	0.43
NT	Ungrazed	–	8.85	6.95	5.28	7.02	5.89	13.23	7.49	14.13	10.19
	Grazed	–	0.91	0.60	0.04	0.52	0.98	0.90	0.20	1.26	0.83
$LSD_{(P=0.05)}$		–	1.52*	1.12	1.70	0.79*	1.05	4.72*	2.60	4.98*	1.71*

A priori mean comparisons are between tillage systems within a cover crop management or between cover crop management within a tillage system. *Next to LSD value indicates significance in at least one of these comparisons.

immediately following planting. Lower early-season pearl millet population under NT than under CT, however, was not a hindrance to successful cover crop dry matter accumulation (Table 4). These results suggest that pearl millet could possibly be planted at lower density than the 13–17 $kg\,ha^{-1}$ rate that was targeted in this study.

The only other major tillage effect was that the corn population under NT in 2005 was $23 \pm 2\%$ greater than under CT (Table 3). The water conservation benefit of NT compared with CT may have contributed to this effect, as well as the fact that corn was planted a week earlier under NT than under CT (Table 1). The earlier planting date was a consequence of greater preparation time required for CT planting.

The only cover crop management effect on plant population occurred with wheat (Table 3). More plants were established with grazing than without grazing of cover crops under NT in 2003. Inhibition of seedling emergence could have occurred with the large amount of pearl millet residue at the soil surface, because of either a mechanical cause at planting from residue impeding penetration of planting equipment into the soil or from a biochemical cause at seedling emergence due to presence of allelopathic compounds[22].

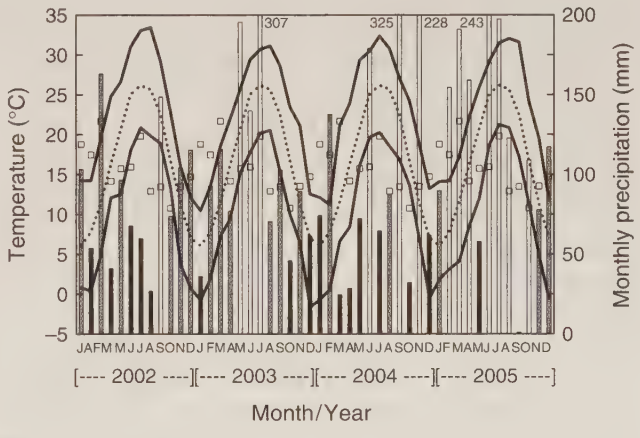


Figure 1. Monthly temperature and precipitation near Watkinsville, GA from 2002 to 2005. Solid lines are observed minimum and maximum temperatures and dotted line is the long-term (1945–2003) mean temperature. Vertical bars are observed monthly precipitation, and squares are long-term mean precipitation. Vertical bars that are gray-shaded are within 75–125% of mean precipitation. Vertical bars that are black are <75% of mean precipitation. Vertical bars that are unfilled are >125% of mean precipitation. Data from the Georgia Automated Environmental Monitoring Network (www.georgiaweather.net).

Summer grain-crop production

Summer grain-crop production was highly variable from year-to-year (Table 4). Precipitation from May to September was also highly variable (Figs. 1 and 2). During 2002, precipitation from sorghum planting to grain filling in mid September was only 121 mm, well below that needed to produce a crop. Sorghum production during 2003 was more typical of the regional average, and was not affected by tillage or cover crop management. Sorghum production in 2004 was again very low, because of late-season precipitation in September (Fig. 2), which caused lodging

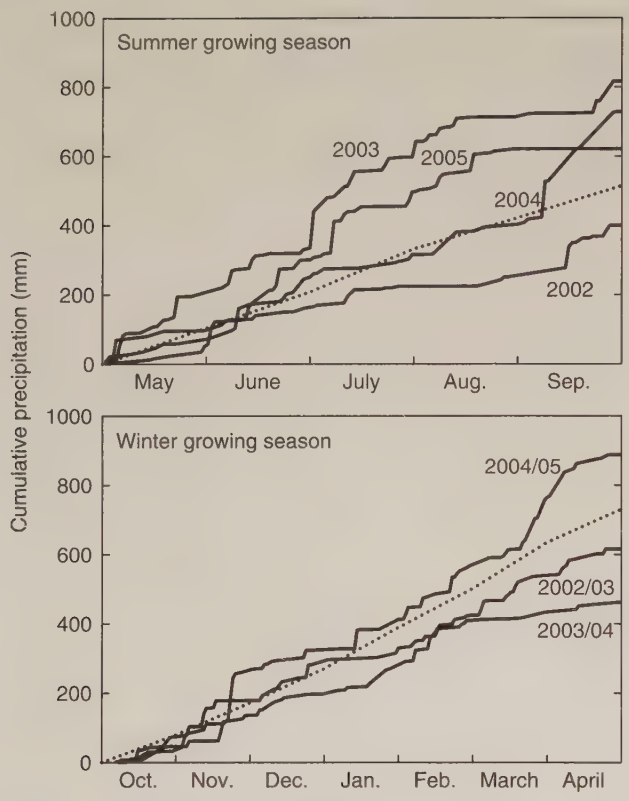


Figure 2. Cumulative precipitation in summer and winter growing seasons from 2002 to 2005 at Watkinsville, GA. Dotted line is long-term mean cumulative precipitation. Data from the Georgia Automated Environmental Monitoring Network (www.georgiaweather.net).

and made it difficult to harvest grain. The switch to corn production in 2005 (because of poor performance of sorghum in previous years) resulted in very good grain yield, but there was no effect of tillage or cover crop management.

The effect of tillage on grain yield was significant in 2 of 4 years (Table 4). Sorghum grain yield was negatively affected by NT compared with CT in 2002, but was positively affected by NT compared with CT when the cover crop was not grazed in 2004. The effect of cover crop management was significant only in 2004 under NT, in which grazing of cover crop led to lower sorghum grain yield than when cover crop was not grazed. The 4-year mean grain yield was greater under NT than under CT when the rye cover crop was not grazed. In addition, the 4-year mean grain yield was lower when rye was grazed than left ungrazed, but only under NT. The accumulation of surface plant residue under NT appears to have been more important for summer grain production than processing of cover crop into animal manure. Soil water conservation under a mulch of surface residues probably benefited plant production during the summer[23]. Further research is needed to better understand the interaction between tillage and cover crop management on summer grain yield.

Hand-harvested sorghum grain yield in 2004 (Table 5) was 8.4 ± 2.4 times greater than grain yield from commercial-sized farm machinery (Table 4). Hand-harvested corn yield in 2005 was $48 \pm 6\%$ higher than by combine. For sorghum, the large discrepancy between hand- and machine-harvested estimates was due to late-season precipitation that flattened the maturing crop. For corn, higher hand-harvested yield than machine yield was due to grain loss through the machine. Grain-to-whole plant ratio of sorghum in 2004 was 0.48 and of corn in 2005 was 0.56 (Table 5).

Hand-harvested yield of sorghum stover in 2004 (Table 5) was very similar in magnitude to the sorghum standing in the field after combine harvest (Table 4). Standing, summer-crop dry matter after harvest averaged $2.0\,Mg\,ha^{-1}$ in 2002, $4.7\,Mg\,ha^{-1}$ in 2003, $5.9\,Mg\,ha^{-1}$ in 2004, and $8.7\,Mg\,ha^{-1}$ in 2005. Standing summer-crop dry matter was not affected by tillage in 2002, but was significantly greater under NT than under CT in all other years. The 4-year mean values followed the order: NT-ungrazed>NT-grazed>CT-ungrazed = CT-grazed. It appears likely that a soil water conservation effect contributed to higher production with NT compared with CT and, under NT, with surface crop residue accumulation compared with grazed condition.

The results for summer crop grain yield in this study were in general agreement with previous studies, in which grain yield was positively affected by NT compared with CT[10–12]. However, there is little available literature describing the effect of grazing cover crops on subsequent grain yield. Our results indicate that grazing of rye as a winter cover crop negatively affected 4-year mean summer grain and stover production under NT, but not under CT (Table 4).

Winter grain-crop production

Winter wheat production was highly uniform, both among years and within years among treatments (Table 4). Tillage and cover crop management had no effect on wheat grain yield in any year. Precipitation was nearly as variable in winter as in summer (Fig. 2), but the low evaporative demand allowed wheat to develop successfully despite differences in precipitation. Variation in wheat grain yield among years (8%) was much lower than variation in summer grain yield (85%). Mean wheat grain yield averaged $2.7\,Mg\,ha^{-1}$, while summer grain yield averaged $3.3\,Mg\,ha^{-1}$. These data support the hypothesis that winter grain production would be more uniform, but lower in potential, than summer grain production, as a result of differences in climatic conditions between winter and summer.

Standing wheat dry matter after harvest was greater with grazed than with ungrazed cover crop in 2005 and when averaged across years, independent of tillage system (Table 4). This cover crop management effect may have been due to either (1) enhanced nutrient availability to wheat with processing of summer cover crop dry matter through grazing cattle as manure or (2) inhibition of wheat

Table 5. Hand-harvested yield components of three grain crops managed with either CT or NT and with or without cattle grazing of cover crops.

		Wheat (28 May 2004)			Sorghum (20 September 2004)			Corn (14 September 2005)				
Tillage	Cover crop	Grain	Stover	Grain : Plant	Grain	Stover	Grain : Plant	Grain	Stover	Grain : Plant	Stalks	Ears
		----Mg ha^{-1}----		----g g^{-1}----	-------Mg ha^{-1}-------		----g g^{-1}----	-------Mg ha^{-1}-------		----g g^{-1}----	Number m^{-2}	
CT	Ungrazed	3.39	3.45	0.50	4.51	5.08	0.46	10.08	7.24	0.60	34	33
	Grazed	3.33	4.08	0.45	3.43	4.80	0.39	10.87	7.50	0.60	37	37
NT	Ungrazed	3.30	4.61	0.42	7.77	7.61	0.49	12.78	11.92	0.51	40	40
	Grazed	3.35	4.24	0.44	6.58	5.16	0.58	9.65	8.29	0.54	40	38
$LSD_{(P = 0.05)}$		1.07	1.34	0.04*	3.89	3.43	0.16*	2.25*	3.97*	0.12	11	9

A priori mean comparisons are between tillage systems within a cover crop management or between cover crop management within a tillage system. * Next to LSD value indicates significance in at least one of these comparisons.

growth from unaltered summer cover crop dry matter accumulation. Potential inhibition of wheat stover production could have been from a biochemical cause resulting from either (1) presence of allelopathic compounds in pearl millet or (2) enhanced immobilization of N from mature pearl millet residue straw (although C : N ratio of mature, ungrazed pearl millet residue among years was moderate at 36 ± 15 g g^{-1}; Table 6). Potential inhibition of wheat stover production could have also been physical, at least under NT, resulting from cooler and wetter soil conditions that were likely under heavy mulch residue.

Hand-harvested wheat yield components in 2004 suggested that $32 \pm 20\%$ of wheat grain may have been left in the field, as a result of machine inefficiency (Tables 4 and 5). Standing wheat dry matter (Table 4) would also have to be considered a minimum value, since hand-harvested yield of wheat stover (Table 5) was 4.0 ± 0.5 times greater than machine-harvested stover in 2004 (Table 4). Grain-to-whole plant ratio of wheat averaged 0.45 and was highest under CT when the cover crop was not grazed.

Winter grain crop yields in this study were in general agreement with previous studies, in which grain yield was little affected by tillage system[5,10–12]. There is no known literature describing the effect of grazing summer cover crops on subsequent wheat grain yield. Our results indicate that grazing of pearl millet as a summer cover crop could enhance wheat stover production and have no detrimental effect on wheat grain yield. Tanaka et al.[24] observed that swath grazing by cattle increased forage and grain production compared with cropping systems without cattle during the 4th year of a study in North Dakota. Additional crop responses to grazing of cover crops under different soil and crop management conditions are needed to bolster these results prior to making wide-scale recommendations.

Grain protein

Protein concentration of harvested grain varied from year-to-year and among crops. Across years and crops (wheat, sorghum, and corn), grain protein concentration was 108 ± 16 mg g^{-1}. Grain protein concentration was little affected by tillage and cover crop management, except for wheat in 2004 (Table 6). Wheat grain protein concentration was greater under NT than under CT in 2004 and when averaged across years, perhaps as a result of greater access to soil moisture with surface mulching and preservation of high surface soil organic N with NT (A.J. Franzluebbers, unpublished data). Summarized from a number of studies[25], wheat grain protein concentration varied from 80 to 140 mg g^{-1}. Halvorson et al.[26] reported grain protein concentration of 139 ± 31 mg g^{-1} during 9 years of cropping with wheat–corn–fallow and wheat–sorghum–fallow in Colorado. Sorghum and corn grain protein concentration was 127 ± 11 mg g^{-1} among nine selections in Kansas[27].

Table 6. Grain protein concentration and C : N ratio of plant residues in two cropping systems managed with either CT or NT and with or without cattle grazing of cover crops.

		Summer grain/winter cover crop					Winter grain/summer cover crop				
Tillage	**Cover crop**	**2002**	**2003**	**2004**	**2005**	**Mean**	**2002**	**2003**	**2004**	**2005**	**Mean**
Grain protein ($mg\,g^{-1}$)		----------Sorghum (2002–2004) or corn (2005) ----------					----------Wheat----------				
CT	Ungrazed	124	88	115	93	105	–	121	106	95	108
	Grazed	124	85	143	92	111	–	117	115	98	110
NT	Ungrazed	127	95	107	95	106	–	124	127	100	117
	Grazed	127	93	114	90	106	–	122	130	101	118
$LSD_{(P=0.05)}$		10	11	35	7	9	–	15	11*	6	6*
C : N ratio of grain-crop standing dry matter ($g\,C\,g^{-1}\,N$)		----------Sorghum (2002–2004) or corn (2005) ----------					----------Wheat----------				
CT	Ungrazed	32	61	30	41	41	–	83	100	134	106
	Grazed	31	46	29	39	36	–	71	95	119	95
NT	Ungrazed	34	51	28	48	40	–	68	70	127	88
	Grazed	33	57	31	39	40	–	70	82	127	93
$LSD_{(P=0.05)}$		7	12*	7	12	4*	–	14*	39	32	16*
C : N ratio of cover crop standing dry matter ($g\,C\,g^{-1}\,N$)		----------Rye----------					----------Pearl millet----------				
CT	Ungrazed	–	45	47	19	37	58	21	33	21	33
	Grazed	–	39	29	8	25	17	18	21	15	18
NT	Ungrazed	–	55	59	17	44	57	26	39	29	38
	Grazed	–	41	50	10	34	23	20	17	20	20
$LSD_{(P=0.05)}$		–	9*	18*	4*	6*	14*	5*	5*	5*	4*

A priori mean comparisons are between tillage systems within a cover crop management or between cover crop management within a tillage system. *Next to LSD value indicates significance in at least one of these comparisons.

Cover crop production

Ungrazed rye cover crop production was significantly greater under NT than under CT in 2003 (Table 4). Although differences were not significant in subsequent years, there was a continuing trend for higher production with NT than with CT. Averaged across years, ungrazed rye cover crop production was 6.0 Mg ha^{-1} under CT and 7.0 Mg ha^{-1} under NT ($P = 0.03$). Cattle grazing rye cover crop were able to consume 95 ± 4% of the forage by the end of the growing season (difference in cover crop standing dry matter between ungrazed and grazed plots). Standing dry matter of rye following grazing did not vary between tillage systems, averaging 0.4 ± 0.4 Mg ha^{-1} across years and tillage systems.

Ungrazed pearl millet cover crop production was significantly greater under NT than under CT in 2003 and 2005 (Table 4). Averaged across years, ungrazed pearl millet cover crop production was 7.6 Mg ha^{-1} under CT and 10.2 Mg ha^{-1} under NT ($P = 0.01$). Cattle grazing pearl millet cover crop consumed 93 ± 4% of the forage produced. Standing dry matter of pearl millet following grazing did not vary between tillage systems, averaging 0.6 ± 0.4 Mg ha^{-1} across years and tillage systems. It is clear from the data in our study that NT was superior to CT for producing cover crop growth.

The C : N ratio of ungrazed cover crops was higher than the remaining cover crop biomass at the end of grazing for both cover crop types and in all years (Table 6). Ungrazed cover crop C : N ratio was often greater under NT than under CT, which may have been due simply to greater biomass accumulation with NT. In contrast, the C : N ratio of wheat stover was lower under NT than under CT when the previous cover crop was ungrazed. The reason for this discrepancy in C : N ratio between cover crops and grain crops with respect to tillage is unclear.

Cover crops grazed by cattle were transformed from (a) raw plant materials that could be used to help conserve soil water and protect the soil surface from erosion into (b) non-uniform animal manure droppings that could contribute to accelerated nutrient cycling and more rapid transformation of crop residue into soil organic matter. Characterizing the benefits of ungrazed and grazed cover crops on ecosystem processes extending beyond the growth of plants needs further investigation.

Greater cover crop production with NT compared with CT suggests that there would be no need to invert crop residues and soil to obtain adequate cover crop growth. Any standing weeds prior to establishment of a cover crop could be controlled with preplant herbicide. Post-planting weeds could be effectively controlled with the development of a vigorous cover crop canopy.

Cattle stocking characteristics

Cattle were stocked on rye for 26–49 days in the spring and on pearl millet for 31–77 days in the summer (Table 2). During the first year of experimentation, yearling steers (5.9–6.7 head ha^{-1}) were stocked on both pearl millet and rye and in subsequent years cow/calf pairs (3.1–5.5 pair ha^{-1}) were stocked on cover crops. Average suckling-calf head weight was lower on rye (69–92 kg head^{-1}) than on pearl millet (182–224 kg head^{-1}), because all calves were born in January/February of each year and rye was ready for grazing about 2 months after calving whereas pearl millet was ready for grazing about 5 months after calving. Average cow weight was not different between cropping systems (515 ± 19 kg head^{-1}).

Total weight of cattle on rye varied from a low of 1.74 Mg ha^{-1} in 2003 to a high of 2.72 Mg ha^{-1} in 2004, averaging 2.36 Mg ha^{-1} across years (Table 2). On pearl millet, stocking weight varied from a low of 1.89 Mg ha^{-1} in 2003 to a high of 2.94 Mg ha^{-1} in 2004, averaging 2.50 Mg ha^{-1} across years. Although no differences occurred between tillage systems in any one particular year, stocking weight tended to be greater under NT than under CT when averaged across years and cover crops ($P = 0.09$), reflecting the greater availability of forage under NT than under CT.

Total number of grazing days was 302 ± 119 (head d) ha^{-1} on rye and 390 ± 79 (head d) ha^{-1} on pearl millet (Table 2). The greater number of grazing days on pearl millet was due to greater forage production (Table 4) and regrowth potential. Number of grazing days was greater under NT than under CT when averaged across years on rye, but was not different between tillage systems on pearl millet. Significant tillage effects did occur in 2002 and 2005 on pearl millet, but they were opposing, resulting in no difference across years.

Cattle performance and production

Calf daily gain was excellent on both forages, but was higher on rye (2.18 ± 0.18 kg head^{-1} d^{-1}) than on pearl millet (1.93 ± 0.17 kg head^{-1} d^{-1}) (Table 7). Calf daily gain tended to be higher under NT than under CT in most years, but differences were not significant for any year. Averaged across years, calf daily gain was significantly higher under NT than under CT on pearl millet (13%) and when averaged across cover crops (2.16 versus 1.95 kg head^{-1} d^{-1}; $P = 0.01$).

Cow daily gain was highly variable among years and tillage systems (0.88 ± 1.16 kg head^{-1} d^{-1}) (Table 7), partly because of variable weather conditions (e.g., 121 ± 36% of normal precipitation during the five growing seasons with cows) and variable length of grazing period (44 ± 12 days during the five seasons). Considering both cows and calves together, average daily gain across years was greater under NT than under CT on rye (36%) and when averaged across cover crops (1.80 versus 1.45 kg head^{-1} d^{-1}; $P = 0.05$). Greater cattle performance under NT was probably related to greater availability of forage, since stocking rate was mostly similar between tillage systems due to the small

Table 7. Cattle performance and production characteristics in two cropping systems managed with either CT or NT.

	Summer grain/winter cover crop—rye				Winter grain/summer cover crop—pearl millet				
Tillage	**2003**	**2004**	**2005**	**Mean**	**2002**	**2003**	**2004**	**2005**	**Mean**
Calf daily gain (kg head^{-1} d^{-1})									
CT	1.90	2.18	2.18	2.09	1.74	1.94	1.75	1.81	1.81
NT	2.25	2.11	2.45	2.27	2.01	2.14	1.89	2.18	2.05
$LSD_{(P=0.05)}$	0.55	0.45	0.50	0.25	0.39	0.67	0.55	0.68	0.25*
Cow daily gain (kg head^{-1} d^{-1})									
CT	–	1.45	−0.95	0.25	–	1.05	−0.55	2.22	0.91
NT	–	2.42	0.27	1.35	–	1.30	−0.08	1.73	0.98
$LSD_{(P=0.05)}$	–	1.76	1.89	1.15	–	1.89	1.27	1.06	0.72
Cow/calf pair daily gain (kg head^{-1} d^{-1})									
CT	1.90	1.81	0.62	1.44	1.74	1.49	0.60	2.01	1.46
NT	2.25	2.26	1.36	1.96	2.01	1.72	0.91	1.95	1.65
$LSD_{(P=0.05)}$	0.55	0.86	0.91	0.39*	0.39	1.20	0.63	0.67	0.33
Calf gain (kg ha^{-1})									
CT	239	165	124	176	452	184	175	113	231
NT	283	285	147	239	456	209	189	181	258
$LSD_{(P=0.05)}$	69	160	34	51*	101	75	55	57*	31
Cow gain (kg ha^{-1})									
CT	–	133	−48	43	–	102	−55	137	61
NT	–	319	16	167	–	126	−8	143	87
$LSD_{(P=0.05)}$	–	203	111	103*	–	184	127	74	66
Cow/calf pair gain (kg ha^{-1})									
CT	239	298	76	204	452	286	120	250	277
NT	283	604	163	350	456	335	181	324	324
$LSD_{(P=0.05)}$	69	348	120	107*	101	240	125	97	64

* Next to LSD value indicates significance between tillage means.

paddock size that limited our ability to make fine-tuned adjustments.

Calf gain ha^{-1} was 207 ± 71 kg ha^{-1} on rye and was 245 ± 132 kg ha^{-1} on pearl millet (Table 7). There was a tendency for greater calf gain ha^{-1} under NT than under CT in most seasons, but this effect was significant only on pearl millet in 2005. Averaged across years, there was significantly greater calf gain ha^{-1} under NT than under CT on rye (36%) and a tendency for greater calf gain ha^{-1} under NT than under CT on pearl millet (12%; $P = 0.08$).

Cow gain ha^{-1} was highly variable (87 ± 113 kg ha^{-1}), but averaged across years was greater under NT than under CT on rye ($P = 0.02$) with a similar tendency averaged across cover crops ($P = 0.08$) (Table 7). Considering cows and calves together, total gain ha^{-1} was greater under NT than under CT on rye (350 versus 204 kg ha^{-1}; $P = 0.01$) and when averaged across cover crops (337 versus 241 kg ha^{-1}; $P = 0.03$).

Integrated economic analysis

Grain-crop costs were US$284 ± 137 ha^{-1} among years in the summer grain/winter cover crop system and US$237 ± 93 ha^{-1} among years in the winter grain/summer cover crop system (Table 8). First-year costs were higher than subsequent years in both systems, due to extra pasture termination costs. Also when corn replaced sorghum in the summer grain/winter cover crop system, higher fertilizer inputs and use of glyphosate-resistant seed resulted in a doubling of input cost. By excluding cover crop input costs from these estimates, net return from grain cropping only over variable costs was US$40 ± 38 ha^{-1} among tillage and cover crop treatments in the summer grain/winter cover crop system and US$8 ± 21 ha^{-1} among treatments in the winter grain/summer cover crop system. When cover cropping costs were included, all systems resulted in a net loss from grain cropping.

The added value of cattle gain from grazing of cover crops was 138 ± 36% of grain cropping only (Table 8). Obviously with different prices of crop and livestock components, shifts in return could be expected. During the seven seasons evaluated in this study, net return over variable costs was not different between tillage systems in either cropping system. Net return over variable costs was highly significant ($P < 0.01$) between cover crop management systems, averaging −US$63 ha^{-1} when not grazed and US$302 ha^{-1} when grazed.

Increased diversity of income and greater magnitude of economic return when cover crops were grazed by cattle should be key drivers for producers considering the adoption of such a management system. However, with multiple enterprises there will be a need for a greater

Table 8. Mean yearly economic inputs and outputs from summer grain/winter cover crop and winter grain/summer cover crop systems as affected by tillage and cover crop management.

	Sorghum (corn)/rye				Wheat/pearl millet			
	Ungrazed		Grazed		Ungrazed		Grazed	
Item	CT	NT	CT	NT	CT	NT	CT	NT
	US$ ha^{-1}							
Grain crop seed	41.84	43.32	41.84	43.32	43.42	49.20	43.42	49.20
Lime	22.95	22.95	22.95	22.95	30.58	30.58	30.58	30.58
Fertilizer	96.63	96.63	96.63	96.63	50.59	50.59	50.59	50.59
Herbicide	21.34	70.99	21.34	70.99	0.00	79.04	0.00	79.04
Fuel	38.61	15.22	38.61	15.22	41.82	13.07	37.37	11.12
Machinery repair and maintenance	51.35	20.23	51.35	20.23	55.62	17.36	49.72	14.80
Drying	12.08	15.14	13.02	11.61	9.90	10.20	9.44	9.66
Total grain crop variable costs	284.80	284.48	285.74	280.95	231.93	250.04	221.12	244.99
Cover crop seed	58.86	61.58	58.86	61.58	20.78	19.36	20.78	19.36
Fertilizer	50.59	50.59	50.59	50.59	50.99	50.99	50.99	50.99
Total cover crop variable costs	109.45	112.17	109.45	112.17	71.77	70.35	71.77	70.35
Total costs	394.25	396.65	395.19	393.12	303.70	320.39	292.89	315.34
Crop value	301.66	378.23	325.42	290.23	247.42	235.89	255.03	241.64
Added calf gain value	0.00	0.00	290.40	394.35	0.00	0.00	381.15	425.70
Total crop and calf value	301.66	378.23	615.82	684.58	247.42	235.89	636.18	667.34
Net return over variable costs	−92.59	−18.42	220.63	291.46	−56.28	−84.50	343.29	352.00

Unit costs of US$2.65 kg^{-1} sorghum seed, US$5.86 kg^{-1} corn seed, US$0.40 kg^{-1} wheat seed, US$0.49 kg^{-1} rye seed, US$1.23 kg^{-1} pearl millet seed, US$33.07 Mg^{-1} lime, US$1.06 kg^{-1} fertilizer N, US$0.72 kg^{-1} fertilizer P_2O_5, US$0.54 kg^{-1} fertilizer K_2O, US$12.68 l^{-1} glyphosate, US$3.01 l^{-1} atrazine, US$31.17 l^{-1} metolachlor, US$0.59 l^{-1} diesel fuel, and US$3.94 Mg^{-1} grain to dry three points.
Unit values of US$98.42 Mg^{-1} sorghum, corn, or wheat grain produced and US$1.65 kg^{-1} calf gain.
Note: Analysis excludes labor cost, as well as grazing time and gain of cows.

amount of infrastructure, technology, labor and information. The rudimentary economic analysis presented here has not accounted for all of the limitations in an integrated crop–livestock system, but has shown the great potential for economic gain for producers that can effectively optimize such a system within the biophysical and socioeconomic constraints in the southeastern USA. In the Northern Plains region of the USA, winter feeding cost was reduced from US$0.73 cow^{-1} d^{-1} with baled hay in drylot to US$0.49 cow^{-1} d^{-1} with swath grazing of crop residues left in the field[28].

Conclusions

As expected, grain production in the summer was greater, but more variable than in the winter (3.3 Mg ha^{-1} with 94% coefficient of variation among years in summer compared with 2.7 Mg ha^{-1} with 3% coefficient of variation among years in winter). Although precipitation varied equally as much in both summer and winter seasons, lack of precipitation with high evaporative demand throughout the summer and excessive precipitation just prior to harvest caused major reductions in summer grain yield. Summer grain and stover production were greater under NT than under CT, but winter grain and stover production were unaffected by tillage system. In addition, both winter and summer cover crops were more productive under NT than under CT. Grazing cover crops with cattle had (1) a positive effect on wheat stover production irrespective of tillage system, (2) no effect on wheat grain and sorghum (or corn) grain and stover production under CT, and (3) a negative effect on sorghum (or corn) grain and stover production under NT. Both rye and pearl millet cover crops provided an abundant and high-quality diet for either yearling calves or cow–calf pairs for 26–77 days. Calf performance on cover crops was 2.15 ± 0.18 kg head^{-1} d^{-1} under NT, which was an average of 11% greater than under CT. These data indicate that integrated crop–livestock production may not necessarily suppress crop yields, but could even enhance yields and net economic return, especially if managed with conservation tillage. Despite current social challenges with integrated crop–livestock production systems, significant agronomic and economic benefits could be expected with adoption.

Acknowledgements. We acknowledge the excellent technical contributions of Steve Knapp, Eric Elsner, Dwight Seman, Devin Berry, Kim Lyness, Stephanie Steed, Faye Black, Heather Hart, Robert Sheats and Robert Martin. This study was partially

supported by funding from the United States Department of Agriculture (USDA)–National Research Initiative Competitive Grants Program, Agreement No. 2001-35107-11126 and the Georgia Agricultural Commodity Commission for Corn.

References

1 Gates, R.N. 2003. Integration of perennial forages and grazing in sod based crop rotations. In Proceedings of the Sod Based Cropping Systems Conference, 20–21 February 2003, Quincy, FL. p. 7–14.

2 Gliessman, S.R. 1998. Agroecology: Ecological Processes in Sustainable Agriculture. Ann Arbor Press, Chelsea, MI. p. 357.

3 Follett, R.F., Stewart, J.W.B., and Cole, C.V. 1987. Soil fertility and organic matter as critical components of production systems. Soil Science Society of America Special Publication 19, Madison, WI.

4 Franzluebbers, A.J., Stuedemann, J.A., Schomberg, H.H., and Wilkinson, S.R. 2000. Soil organic C and N pools under long-term pasture management in the Southern Piedmont, USA. Soil Biology and Biochemistry 32:469–478.

5 Langdale, G.W., West, L.T., Bruce, R.R., Miller, W.P., and Thomas, A.W. 1992. Restoration of eroded soil with conservation tillage. Soil Technology 5:81–90.

6 Franzluebbers, A.J., Hons, F.M., and Saladino, V.A. 1995. Sorghum, wheat and soybean production as affected by long-term tillage, crop sequence and N fertilization. Plant and Soil 173:55–65.

7 Wagger, M.G. and Denton, H.P. 1989. Tillage effects on grain yields in a wheat, double-crop soybean, and corn rotation. Agronomy Journal 81:493–498.

8 Karlen, D.L. and Gooden, D.T. 1987. Tillage systems for wheat production in the southeastern Coastal Plains. Agronomy Journal 79:582–587.

9 Frederick, J.R. and Bauer, P.J. 1996. Winter wheat responses to surface and deep tillage on the southeastern Coastal Plain. Agronomy Journal 88:829–833.

10 Langdale, G.W., Hargrove, W.L., and Giddens, J. 1984. Residue management in double-crop conservation tillage systems. Agronomy Journal 76:689–694.

11 Cassel, D.K. and Wagger, M.G. 1996. Residue management for irrigated maize grain and silage production. Soil and Tillage Research 39:101–114.

12 Hargrove, W.L. 1985. Influence of tillage on nutrient uptake and yield of corn. Agronomy Journal 77:763–768.

13 Edwards, J.H., Thurlow, D.L., and Eason, J.T. 1988. Influence of tillage and crop rotation on yields of corn, soybean, and wheat. Agronomy Journal 80:76–80.

14 Groffman, P.M., Hendrix, P.F., and Crossley, D.A. Jr 1987. Nitrogen dynamics in conventional and no-tillage agroecosystems with inorganic fertilizer or legume nitrogen inputs. Plant and Soil 97:315–332.

15 Sainju, U.M. and Singh, B.P. 2001. Tillage, cover crop, and kill-planting date effects on corn yield and soil nitrogen. Agronomy Journal 93:878–886.

16 Schwab, E.B., Reeves, D.W., Burmester, C.H., and Raper, R.L. 2002. Conservation tillage systems for cotton in the Tennessee Valley. Soil Science Society of America Journal 66:569–577.

17 Tollner, E.W., Calvert, G.V., and Langdale, G. 1990. Animal trampling effects on soil physical properties of two southeastern U.S. Ultisols. Agriculture, Ecosystems and Environment 33:75–87.

18 Franzluebbers, A.J. and Stuedemann, J.A. 2005. Soil carbon and nitrogen pools in response to tall fescue endophyte infection, fertilization, and cultivar. Soil Science Society of America Journal 69:396–403.

19 Ashford, D.L. and Reeves, D.W. 2003. Use of a mechanical roller-crimper as an alternative kill method for cover crops. American Journal of Alternative Agriculture 18:37–45.

20 Schomberg, H.H., Stuedemann, J.A., Franzluebbers, A.J., and Wilkinson, S.R. 2000. Spatial distribution of extractable phosphorus, potassium, and magnesium as influenced by fertilizer and tall fescue endophyte status. Agronomy Journal 92:981–986.

21 SAS Institute. 2002. SAS for Windows, Version 9.1. SAS Institute, Cary, NC.

22 Saxena, A., Singh, D.V., and Joshi, N.L. 1996. Autotoxic effects of pearl millet aqueous extracts on seed germination and seedling growth. Journal of Arid Environments 33: 255–260.

23 Hatfield, J.L., Sauer, T.J., and Prueger, J.H. 2001. Managing soils to achieve greater water use efficiency. A review. Agronomy Journal 93:271–280.

24 Tanaka, D.L., Karn, J.F., Liebig, M.A., Kronberg, S.L., and Hanson, J.D. 2005. An integrated approach to crop/livestock systems: forage and grain production for swath grazing. Renewable Agriculture and Food Systems 20: 223–231.

25 Makowski, D., Wallach, D., and Meynard, J.-M. 1999. Models of yield, grain protein, and residual mineral nitrogen responses to applied nitrogen for winter wheat. Agronomy Journal 91:377–385.

26 Halvorson, A.D., Nielsen, D.C., and Reule, C.A. 2004. Nitrogen fertilization and rotation effects on no-till dryland wheat production. Agronomy Journal 96:1196–1201.

27 Kriegshauser, T.D., Tuinstra, M.R., and Hancock, J.D. 2006. Variation in nutritional value of sorghum hybrids with contrasting seed weight characteristics and comparisons with maize in broiler chicks. Crop Science 46:695–699.

28 Karn, J.F., Tanaka, D.L., Liegig, M.A., Ries, R.E., Kronberg, S.L., and Hanson, J.D. 2005. An integrated approach to crop/livestock systems: wintering beef cows on swathed crops. Renewable Agriculture and Food Systems 20:232–242.

Renewable Agriculture and Food Systems: 22(3); 181–188 doi:10.1017/S174217050700172X

Hedgerow barriers and other reduced-risk controls for managing Oriental fruit moth, *Grapholitha molesta* (Busck) (Lepidoptera: Tortricidae) in apples

Carlos Garcia-Salazar[1,*], Larry J. Gut[2], and Mark E. Whalon[2]

[1]Michigan State University Extension, Central Region–Ottawa County, 333 Clinton Street, Grand Haven, MI 49417-1329, USA.
[2]Department of Entomology and Center for Integrated Plant Systems, Michigan State University, East Lansing, MI, USA.
*Corresponding author: garcias4@msu.edu

Accepted 19 September 2006 **Research Paper**

Abstract

Management of Oriental fruit moth, *Grapholitha molesta* (Busck), in apple using an 'Enhanced Integrated Pest Management (IPM)' program comprised of a hedgerow barrier, pheromone-based mating disruption and reduced-risk [non-organophosphorous (OP) or carbamate] insecticides was investigated over a 5-year period. The barrier was comprised of a planting of three rows of hybrid poplar, *Populus deltoides* Bartr. × *Populus nigra* L., one row of Italian alder, *Alnus cordata* L. (nectar reward), and one row of white pine, *Pinus strobus* L. The hedgerow completely surrounded the perimeter of the apple orchard and was treated with garlic and a low rate of pyrethroid insecticide in 4 of the 5 years. The Enhanced IPM program significantly reduced *G. molesta* populations as measured by moth captures in pheromone traps. Captures of *G. molesta* were significantly higher in apple orchards treated with OP and carbamate insecticides, 'Conventional IPM', and either not surrounded by the hedgerow or with the barrier present but not treated with the repellent compounds. To explain these differences in *G. molesta* control, and the potential non-lethal effect of hedgerow barriers on *G. molesta* orchard colonization, we studied the adult vertical movement in a traditional unsprayed standard apple orchard at three different heights: 0.95, 1.95 and 3.20 m, respectively. In the overwintering generation at a height of 0.95 and 1.95 m, the mean number of moths captured per sampling period was 14.64 and 14.84, respectively, and only 2.95 at 3.20 m. However, the number of individuals captured in the second and third generations was not significantly different at the three different heights. Fruit damage evaluated before 'June drop' closely corresponded to the distribution of moths captured during the overwintering generation. Fruit damage at a height of 1.95 and 3.20 m was 5.8 and 3.5%, respectively. These results indicated that *G. molesta* is a weak flyer and that hedgerow barriers exerted some influence in the colonization of the orchard by limiting the free movement of adults from the overwintering generation. Thus, hedgerow barriers seem to limit early migration and establishment of *G. molesta* in the orchard. This in turn may reduce the size of the following generations and makes subsequent control easier under the Enhanced IPM program.

Key words: *Grapholitha molesta*, flight behavior, IPM, live hedgerows, reduced-risk insecticides

Introduction

The Oriental fruit moth (OFM), *Grapholitha molesta* (Busck), is a cosmopolitan insect that causes extensive damage to stone and pome fruit crops worldwide. In 1913, the OFM was first reported in the eastern United States attacking stone fruits, and by 1942 had already reached the West coast peach and nectarine production regions[1]. In the Midwestern United States, OFM was detected in peaches in the mid-1920s, and in recent years, it also has become an important pest problem in apples[2,3]. In Michigan, the OFM, together with the codling moth (CM), *Cydia pomonella* L., redbanded leafroller (RBLR), *Argyrotaenia velutinana* (Walker) and obliquebanded leafroller (OBLR), *Choristoneura rosaceana* (Harris), comprise the main lepidopteran pest complex of peach, pear and apple.

© 2007 Cambridge University Press

The primary tactics for control of this apple pest complex over the past 40 years have been organophosphorous (OP) and carbamate insecticides. These broad-spectrum insecticides remain crucial to pest control in Michigan apple orchards. Therefore, growers may face a crisis if OP and carbamate insecticides are lost due to the emerging regulatory constraints imposed by the Food Quality Protection Act (FQPA) of 1996 (Public Law No. 104–170) and Pesticide Reregistration Implementation Act of 2003 (FIFRA 7 U.S.C. 136 *et seq.*). This situation has been further exacerbated by the increased resistance of key pests such as CM, OBLR, spotted tentiform leafminer, *Phyllonorycter blancardella* (F.), white apple leafhopper, *Typhlocyba pomaria* (McAtee), and rosy apple aphid, *Dysaphis plantaginea* (Passerini), to several common OP insecticides[4–8]. In the absence of OP compounds, synthetic pyrethroids (SP) are the most likely class of insecticides that apple growers will apply to manage insect pests. However, a growing reliance on these broadly toxic and highly disruptive compounds may present yet another threat: secondary pest outbreaks similar to the end of the chlorinated hydrocarbon era and the introduction of SP into tree fruit production[9–11]. New OP insecticide replacements commonly known as reduced-risk insecticides, including imidacloprid, thiamethoxam and indoxacarb, have recently been registered that may provide alternatives to broad-spectrum materials. Although the reduced-risk features of selectivity and minimal contact toxicity inherent to these compounds make them environmentally desirable, the selective nature of these compounds will likely mean that multiple sprays are required to suppress the apple pest complex below economic injury levels[12,13]. In addition, it poses a severe challenge to apple growers facing a complex of pests and a low tolerance for damage. A novel approach to meeting this challenge would be to employ new and innovative strategies that combine the manipulation of the apple agro-ecosystem with the use of new insecticides.

The planting of hedgerows along the perimeter of orchards is a cultural modification that has proved useful in horticultural production. The action of the hedgerow is to slow wind speed and modify the environmental conditions behind the tree barrier. Their main use has been as windbreakers in areas where winds reduce pollination or cause damage to fruit and tree structures[14,15]. In Europe, the value of vegetative buffers for reducing drift potential onto sensitive terrestrial and aquatic areas has been recognized. According to Hewitt[16], the use of windbreakers in the Netherlands's orchards resulted in a reduction in spray drift of 68 to more than 90%. However, living hedgerows have not been well researched for their potential as a pest management strategy by serving as an impediment to immigration or emigration of insects. In addition, the impact of the barrier may be enhanced by treating it with repellents or low rates of insecticides (pyrethroid) to repel or irritate pest species that frequently invade orchards from outside sources, i.e., CM, leafrollers and apple maggot[17–20]. Previous studies on the movement of key insect pests into and out of Michigan fruit orchards demonstrated that plum curculio, *Conotrachelus nenuphar* (Herbst), apple maggot, *Rhagoletis pomonella* (Walsh), and several leafrollers orient their flight below 3 m[18,21–26]. Other species like tarnished plantbug, *Lygus lineollaris* L., pentatomids, leafhoppers, particularly the X-disease vectors *Paraphlepsius irroratus* (Say) and *Scaphytopius acutus* (Say), and rose chafer, *Macrodactylus subspinosus* (Fab.), prefer to fly just above the ground cover in the air boundary layer. Deployment of barriers in experimental peach plots in Michigan revealed that physical net barriers effectively reduced the immigration of aphids and reduced the number of lepidopteran pests (primarily leafrollers) captured in pheromone traps[25,26].

In light of the recent emergence of OFM as a major pest in apple, we initiated studies on the ecology and management of this pest in apple. The primary objective was to compare the population dynamics and management of OFM using broad-spectrum insecticides ('Conventional IPM' program) versus an 'Enhanced IPM' program which relies on hedgerow barriers, selective control tactics which included pheromone mating disruption, reduced-risk insecticides and low rates of pyrethroids applied to the hedgerow barrier. The secondary objective was to determine the impact of hedgerow barriers on the vertical distribution of OFM in an effort to separate the insecticide effects from the non-lethal effects of hedgerow barriers on *G. molesta* control.

Materials and Methods

OFM population dynamics under two pest management regimes

Experimental plots. The study was conducted from 1996 to 2000 at the Michigan State University Clarksville Horticultural Experiment Station (CHES) at Clarksville, MI (latitude: 42.8733 North; longitude: −85.2604 West; elevation: 273 m). This experiment station is located in the west central region of Michigan, at the heart of Michigan's apple growing region. The experimental plots consisted of eight 0.21 ha apple orchards that were established in 1994 to conduct research on novel pest controls in apple. One hundred and four trees of each of three cultivars, 'Ida red'/'Mark', 'Empire'/'M 9 EMLA' and 'Liberty'/'Mark' (cultivar/rootstock), per plot were planted on a 1.5 m within row by 4.5 m spacing. There were four rows per variety, 26 trees in length, running in a north–south direction, and trained to a slender spindle system with a target height of 3.0 m. Each tree was supported by a 2.5 m metal tube and high tensile wire stretched across the row at a 2.2 m height.

The eight small orchards were established as four pairs of plots distributed on the experiment station property such that a distance of at least 100 m separated all pairs. A hedgerow barrier was established surrounding the perimeter of one orchard of each pair. The hedgerow consisted of

Table 1. Treatment arrangement on hedgerow and non-hedgerow apple orchards.

Year	Hedgerow barrier	Non-hedgerow barrier
1996	Enhanced IPM	Conventional IPM
1997	Enhanced IPM	Conventional IPM
1998	Enhanced IPM	Enhanced IPM
1999	Enhanced IPM	Conventional IPM
2000	Conventional IPM	Enhanced IPM

three rows of hybrid poplar, *Populus deltoides* Bartr. × *Populus nigra* L. (adjacent to apples), one row of Italian alder, *Alnus cordata* L. (nectar reward), and one row of white pine, *Pinus strobus* L., surrounding the perimeter of the apple orchard. Alleyways with the hedgerow orchards were planted with the grass mix, 'Crusader' (Seed Research of Oregon, Corvallis, OR), that included rye grass with the endophitic fungus *Acremonium lolii* (Latch, Christensen and Samuels). The purpose of this grass mix was to prevent the establishment of Lygus bug, *L. lineollaris* (Palisot de Beauvois), a major pest of apples in this region. Alleyways within the non-hedgerow orchards were planted with an orchard grass, Kentucky blue grass and fescue mix. This grass cover is common in Michigan's apple orchards. Apple trees and hedgerows were irrigated with a trickle irrigation system. Trees were irrigated during each growing season with scheduling based on satisfying 100% of a 'Class A Evaporative Pan'. Over the 5-year course of the study, apple trees reached a height of ca. 3 m and barriers reached a height of 4–5 m.

Management programs. Two IPM programs were employed for managing OFM, one program based on selective insecticides and mating disruption, and the other based on broad-spectrum insecticides (Tables 1–3). Selective insecticides applied for OFM control included Confirm® (tebufenozide), Intrepid® (methoxyfenozide), Actara® (thiamethoxam), or Avaunt® (indoxacarb). Broad-spectrum insecticides applied for OFM control included Guthion® (azinphosmethyl), Imidan® (phosmet) or Lannate® (methomyl).

In 1996, 1997 and 1999, non-OP selective insecticide treatments and mating disruption were applied in the hedgerow barrier plots. This combination of hedgerows and products will be called hereafter 'Enhanced IPM' program. The traditional OP insecticide treatments were applied in the non-hedgerow plots hereafter called 'Conventional IPM' program (Table 1). The hedgerow barriers were hand-gun treated with Asana® XL (esfenvalerate) at a very low rate of 0.332 liter ha^{-1} every 28 days, with the intent of repelling immigrating OFM and other pests (Tables 1 and 2). The repellent was delivered in 30 l of water per plot at an oblique angle to the outside row of the barrier planting to preclude penetration into the apple orchard. To test the barrier effects and allow for statistical contrasts, the treatments applied to barrier and non-barrier plots were adjusted in 1998 and 2000. In 1998, the 'Enhanced IPM' program was applied to both hedgerow and non-hedgerow barrier plots, with the objective of separating barrier effects from those of the reduced-risk insecticides. In 2000, to assure that hedgerow effects were not due to insecticide treatments, the 'Enhanced IPM' program was applied to non-hedgerow plots and the 'Conventional IPM' program to hedgerow plots. This is in contrast to the 1996, 1997 and 1999 arrangement of treatments.

Arthropod monitoring. Male flight of OFM was monitored weekly from early May to September using pheromone-baited traps. A single delta trap baited with a standard pheromone lure (Scenturion, Inc., Clinton, WA) was placed in the center of each plot. Traps were placed 1.8 m above the ground in the middle portion of the apple tree canopy. Lures were replaced monthly and sticky inserts were changed once per generation.

Experimental design and analysis. As already indicated, the experiment was a paired plot design. Thus, the impact of the treatments, hedgerow and non-hedgerow barrier, and the associated selective or broad-spectrum control tactics, on the OFM adult population was analyzed using a paired *t*-test. Prior to data analysis, weekly moth captures were transformed to $(X+1)^{1/2}$ to normalize the distribution and analyzed using Stat View (Abacus Concepts, Inc., Berkeley, CA).

Vertical movement of OFM

To assess the effect of height on OFM flight behavior, the vertical positioning of the OFM overwintering, second and third generations was measured by placing Delta traps baited with standard red septa lures (Scenturion Inc., Clinton, WA) at three different heights—0.95, 1.95 and 3.20 m—in 2000. This supplemental experiment was conducted in an orchard not treated with insecticides at the Michigan State University Trevor Nichols Research Complex, Fennville, MI (latitude: 42.5951 North; longitude: −86.1561 West; elevation: 214 m). The plot was an 18-year-old Red Delicious orchard (0.550 ha) with trees planted at a distance of 7.0 by 7.0 m in a north–south direction and tree height averaging 6.0 m. The orchard comprised 12 rows of 10 trees each. We selected four rows, two in the center of the orchard and two additional rows proximate to the eastern and western borders of the orchard. The rows served as blocks ($n = 4$ blocks), 21.0 m apart from each other. Each row was divided into three plots, three trees each. A trap-height treatment was assigned randomly to experimental unit trees and subsequently treatments were rotated clockwise after each inspection. A distance of 8–10 m separated the treatment trees or experimental units within each plot. OFM monitoring began in early May and ended in late August. Traps were inspected, and moths were counted and removed, every other day. Lures and sticky trap inserts were replaced at the start of each OFM flight (three changes).

Table 2. Pest management program applied to experimental apple orchards surrounded by hedgerow barriers to control the apple pest complex. Clarksville, MI (1996–1999).

Program	Year	Product	Dates	Target species[2]
Enhanced IPM	1996	Isomate®, 400 dispenser ha^{-1}	Before 1st flight	CM
		Asana® XL, 0.332 l ha^{-1}[1]	5/28, 6/10	LR and PC
		Guardian® (garlic extract)[1] (Barrier only), 0.72 l ha^{-1}	5/17–8/6, wkly	
		Provado®, 0.470 l ha^{-1}	5/17	LR
		Confirm®, 1.05 l ha^{-1}	5/30, 6/10, 6/21, 7/3	LR and CM
Enhanced IPM	1997	Isomate®, 400 dispenser ha^{-1}	Before 1st flight	CM
		Asana® XL, 0.65 l ha^{-1}[1]	6/5, 7/7, 8/8, 8/26	PC and LR
		SpinTor®, 0.325 l ha^{-1}	6/6, 7/7	LRs
		Confirm®, 1.17 l ha^{-1}	8/8, 8/26	CM and AM
Enhanced IPM	1998	Isomate M-100®, 400 dispenser ha^{-1}	Before 1st flight	OFM
		Codlemone®, 2 g ha^{-1} d^{-1} (MSU Microsprayer)	Before 1st flight	CM
		Cumply® 40WP, 0.25 kg ha^{-1}	5/15, 6/3	PC
		Provado® 1.6EC, 0.52 l ha^{-1}	5/15, 6/3	
		Asana® XL, 0.325 l ha^{-1}[1]	6/9–8/18 wkly	LR
Enhanced IPM	1999	Isomate®, 400 dispenser ha^{-1}	Before 1st flight	CM
		OFM Z8-12Ac, 2 g ha^{-1} d^{-1} (MSU Microsprayer)	Before 1st flight	OFM
		Actara® 25 WG, 0.35 kg ha^{-1}	5/18, 6/3	PC
		Asana® XL, 0.582 l ha^{-1}[1]	4//30, 6/4, 7/8, 8/3, 8/31	LR
Conventional IPM	2000	Imidan® 70 WP, 1.8 kg ha^{-1}	5/18, 8/30	PC and CM
		Lorsban 50 WP, 1.0 kg ha^{-1}	7/1	LR, PC and CM
		Imidan® 70 WP, 1.8 kg ha^{-1}	5/18, 6/2	PC and CM

[1] Barrier only.
[2] CM = codling moth; PC = plum curculio; LR = leafrollers; AM = apple maggot; OFM = Oriental fruit moth.

Table 3. Pest management conducted in experimental apple orchards without hedgerow barriers. Clarksville, MI (1996–1999).

Program	Year	Product	Dates	Target species[1]
Conventional IPM	1996	Lannate 90 SP, 1.0 kg ha^{-1}	5/17	LR and aphids
		Lorsban 50 WP, 1.0 kg ha^{-1}	5/27, 7/2	LR, PC, CM and aphids
		Guthion 50 WP, 1.5 kg ha^{-1}	6/10, 6/21, 8/21	LR, CM, PC and AM
Conventional IPM	1997	Lannate 90 SP, 1.0 kg ha^{-1}	6/6	LM and PC
		Lorsban 50 WP, 1.0 kg ha^{-1}	6/16	LR, PC and CM
		Guthion 50 WP, 1.5 kg ha^{-1}	6/26, 7/7, 8/8, 8/26	PC, CM and LR
Enhanced IPM	1998	Isomate M-100®, 400 dispenser ha^{-1}	Before 1st flight	OFM
		Codlemone®, 2 g ha^{-1} d^{-1} (MSU Microsprayer)	Before 1st flight	CM
		Cumply® 40WP, 0.25 kg ha^{-1}	5/15, 6/3	PC
		Provado® 1.6EC, 0.52 l ha^{-1}	5/15, 6/3	
		Asana® XL, 0.325 l ha^{-1}	6/9–8/18 wkly	LR
Conventional IPM	1999	Asana® XL, 1.775 l ha^{-1}	4/30	LR
		Imidan® 70 WP, 1.8 kg ha^{-1}	5/18, 6/2	PC and CM
Enhanced IPM	2000	Actara® 25 WG, 0.35 kg ha^{-1}	5/11, 5/24	PC
		Asana® XL, 1.775 l ha^{-1}	6/2, 7/1, 8/2	PC and CM
		Intrepid 2F, 1.2 l ha^{-1}	7/03	LR and CM

[1] LR = leafrollers; PC = plum curculio; CM = codling moth; AM = apple maggot; OFM = Oriental fruit moth; LM = leafminers.

Table 4. Mean comparison of OFM adult moth captures in pheromone traps from hedgerow barrier orchards versus non-hedgerow treated under either an 'Enhanced' or 'Conventional' IPM program.

Year	Treatment	Treatment mean[1]	Mean diff.	DF	*t*-value	*P*-value
1996	No barrier-Conventional IPM	1.130				
	Barrier-Enhanced IPM	1.027	0.102	75	3.097	0.0028
1997	No barrier-Conventional IPM	1.133				
	Barrier-Enhanced IPM	1.011	0.122	63	2.948	0.0045
1999	No barrier-Conventional IPM	1.292				
	Barrier-Enhanced IPM	1.070	0.222	103	5.796	< 0.0001
1998	No barrier-Enhanced IPM	1.360				
	Barrier-Enhanced IPM[2]	1.043	0.317	67	4.502	<0.0001
2000	No barrier-Enhanced IPM	1.321				
	Barrier-Conventional IPM[3]	1.505	−0.184	75	−2.221	0.0294

[1] Mean OFM adult captures in pheromone traps transformed to SQR($X+1$) for linearization.
[2] Barrier and non-barrier orchard treated alike under the 'Enhanced IPM' program.
[3] Barrier plots treated under the 'Conventional IPM' program; non-barrier orchard treated under the 'Enhanced IPM' program.

OFM fruit damage evaluation. Since pheromone traps provide information only on the distribution of male moths, a different measure was needed to assess female distribution. This was accomplished by inspecting fruit high and low in the tree canopy to determine the distribution of OFM injury, which indirectly measured the distribution of female oviposition sites. The damage assessment was made on 17 June, 2000, a timing that corresponded to end of the emergence of the OFM overwintering generation and before the beginning of the natural physiological fruit thinning process know as 'June drop'. At this time, OFM fruit damage is easily discernable from the damage caused by CM, *C. pomonella* L. During this period, OFM larvae were in the fifth instar or pupating, while CM larvae were in the second or third instar. The fruit evaluation was conducted at two elevations: low, 0.95–1.95 m and high, 3.20 m. Six samples of 50 fruits each were collected per block from six randomly selected individual trees; 25 from the top (high, ~3.20 m) and 25 from the mid section of the tree canopy (low, 0.95–1.95 m).

Statistical analysis. The experiment was established as a randomized block design and moth vertical distribution analyzed as a two-way ANOVA with elevations (0.95, 1.95 and 3.20 m) and blocks ($n = 4$) as the main factors. Fruit damage at the two different elevations was analyzed as a two-way ANOVA in which height (low and high) and blocks were the main factors. Moth captures and fruit damage are not normally distributed, therefore we tested data for independence of the variance from the observations' mean by conducting a preliminary ANOVA analysis to evaluate the assumptions of ANOVA. Trapping data were transformed to $\log(X+1)$ or $(X+1)^{1/2}$ because the variance was not independent of the mean moth catch[27]. Also, percentages of fruit damage were transformed to angular values because proportions or percentages form a binomial rather than a normal distribution[27].

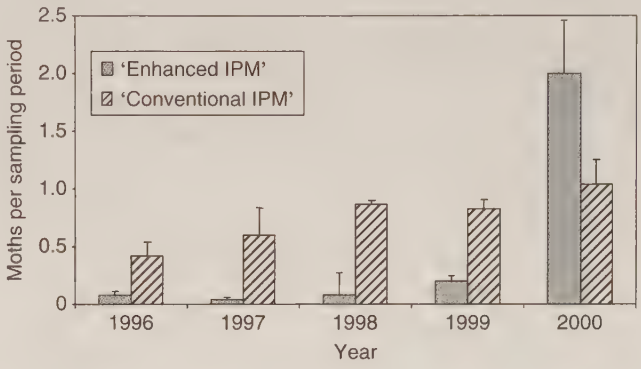


Figure 1. Comparison of the OFM mean moth population captured in pheromone traps placed in apple orchards with hedgerow and non-hedgerow barrier under an 'Enhanced IPM' or 'Conventional IPM' program (1996–2000).

Results

The 'Enhanced IPM' program exhibited a significant ($P \leqslant 0.05$) reduction in adult OFM moth captures in comparison with the 'Conventional IPM' program (Table 4, 1996, 1997, and 1999). In 1998, the reduced-risk materials used in the 'Enhanced IPM' program were applied to both hedgerow and non-hedgerow plots to directly compare the hedgerow effect on moth captures. Under this protocol, again moth captures were significantly lower in the hedgerow than in the no hedgerow plots (Table 4 and Fig. 1). In 2000, the hedgerow plots were treated with the 'Conventional IPM' program, while the 'Enhanced IPM' was applied in the no hedgerow plots. Under this reversal of the treatment protocols followed in 1996, 1997 and 1999, moth captures were significantly higher ($P < 0.05$) in the hedgerow than in the non-hedgerow plots (Table 4 and Fig. 1). This plot reversal yielded an unexpected result that suggested a synergism between the reduced-risk materials and the hedgerow barriers of the 'Enhanced IPM' program.

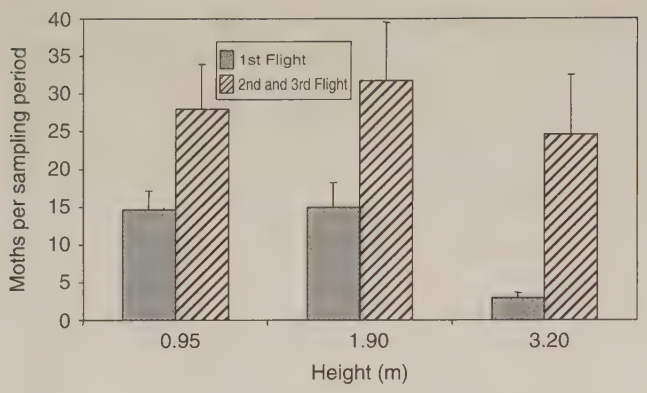


Figure 2. Vertical distribution of adult OFM monitored with pheromone traps at three different heights in a non-pesticide-treated apple orchard.

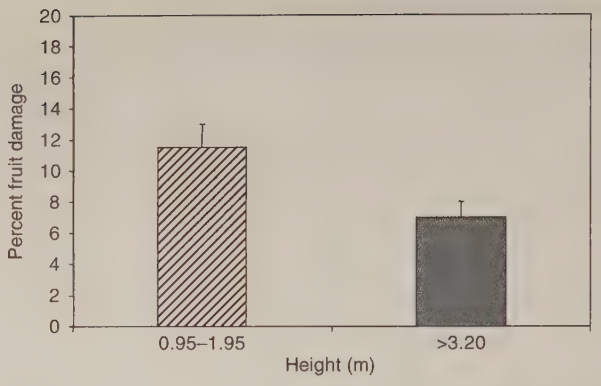


Figure 3. Fruit damage at two different heights caused by the offspring of the OFM overwintering generation in a non-pesticide-treated apple orchard.

Vertical distribution of OFM in apple. Moth captures in traps placed at mid, low or high in the canopy are summarized in Figure 2. During the flight of the overwintering generation, significantly more moths were captured in the two lower canopy positions than in the highest position of 3.2 m ($F = 45.99$; df = 2, 179; $P \leqslant 0.001$). Mean catches of close to 15 moths per trap were recorded at 0.95 or 1.9 m, while fewer than three moths per trap were caught high in the canopy. In contrast, the numbers of individuals captured at all heights in the second and third generations were not significantly different ($P > 0.05$; Fig. 2).

Fruit damage evaluation. Since there was no difference between the two lower positions in moth capture rates, the proportion of fruit damaged was assessed at two heights (0.95–1.95 and >3.20 m) and reflected the average overwintering moth captures. At or above 3.20 m, the mean fruit damage percentage was 7.0 ± 1.1 and below 1.95 m, it was $11.5 \pm 1.5\%$ (mean ± SE) (Fig. 3). The mean difference in fruit injury between the two canopy heights was significant ($F = 5.38$; df = 1, 40; $P = 0.02$).

Discussion

The OFM population densities at CHES research farm during the experimental period were low, 2.0 ± 0.46 per sampling period (mean ± SE). This was in contrast to the population density in the unsprayed plots at the Trevor Nichols Research Complex at Fennville, MI where densities were purposely allowed to reach high levels for experimental purposes, 27 ± 6 per sampling period (mean ± SE). Clarksville OFM moth captures resemble those typically found in Michigan's most intensive apple producing region which surrounds the metropolitan Grand Rapids area (MSU CAT Alerts 1996–2000).

Our research demonstrated that living hedgerows treated with a repellent substantially reduced the population density of OFM in replicated apple orchard trials. This confirms initial findings[25,26] on the potential utility of tree barriers to manage key lepidopteran peach pests. The apparent reluctance of overwintering OFM adults to fly higher than 3.0 m (as demonstrated by the OFM vertical distribution study) may also have contributed to the success of the repellent hedgerow barrier strategy. We believe that most of the individuals trapped in these plots were likely immigrants colonizing the orchards. In the non-hedgerow orchards, immigrant OFM easily penetrated despite the organophosphate-based spray program. On the other hand, immigration into the hedgerow repellent plots required flight over a 3.0–6.0 m high repellent barrier or through a 6 m horizontal living hedge of dense foliage composed of five rows of three different non-host species.

Other Tortricid moths, including the CM and some leafrollers, have exhibited flight behavior above 3.0 m. It has been shown that CM explores the apple tree canopy from 1.0 to 4.0 m above the ground but concentrates its activity in the upper part of the tree canopy, between 3.0 and 3.5 m above the ground[28,29]. The OBLR also exhibits a similar behavior; more mating occurs between 3.0 and 4.0 m above the ground than at the lower part of the apple canopy under 1.0 m[30,31].

In this study, OFM flight behavior was apparently different from that exhibited by the other Tortricid moths. Overwintering adults preferred the mid section of the tree canopy, and <10% of the moths were caught 3.20 m above the ground. The remainder of the moth captures occurred between 0.95 and 1.95 m in the mid-section of the canopy. These results seem to indicate that overwintering OFM adults are weak flyers. Rothschild and Minsk[32,33] found similar OFM moth distribution in peaches, although their study showed that approx. 29% of moths were captured above 2.0 m versus 71% between 1.0 and 2.0 m. In addition, the flight of 2nd and 3rd OFM generations encompassed the whole apple tree canopy. Rothschild and Minsk's[32,33] study suggests that OFM summer generations explore more of the habitat during the mate finding process. We speculate that this change in behavior relates to the physiological conditions of the overwintering individuals. The prolonged arrested development during diapause may reduce the flight capacity of the overwintering generation. Conversely,

summer generation individuals encounter conditions of abundant food and suitable microclimate, thus accumulating greater fat reserves yielding better ovipositional fitness than those experiencing long periods of adverse environmental conditions. Data furnished by Phillips and Proctor[34] infer this conclusion as well. Phillips and Proctor[34] demonstrated that overwintering OFM female fecundity was much lower than that of subsequent summer generations (7.5% versus 14% respectively). In addition, overwintering generation egg to adult mortality apparently reduced the progeny to only 23% of those observed during either summer generations.

This hedgerow repellent system may have important implications for more sustainable, low insecticide orchard pest management. Early establishment of a pest population in the orchard is crucial for the success of the following generations. Therefore, we infer from our results that limiting the number of OFM immigrants reduced the size of the following generations, yielding lower overall seasonal densities. On the other hand, the unexpected results for the reversal of treatments observed in Table 4 support the contribution of the combination of the hedgerow and the reduced-risk materials in the 'Enhanced IPM' program for reducing OFM moth captures.

The observed vertical movement of the overwintering generation as measured by pheromone trap catches supports earlier observations by Hughes and Dorn[35] indicating that the OFM is a relatively weak flyer; most of the population exhibits short flights, 40–400 m long. However, our data indicated that this characterization might only be true for the overwintering generation because the succeeding generations explore the whole tree canopy. This is also an important finding for the deployment of OFM pheromone mating disruption dispensers because the difference in succeeding generation's utilization of the tree may influence dispenser and monitoring trap placement.

In eastern and Upper Midwestern United States orchard production regions, tree fruit producers face accelerated suburban and rural sprawl. Therefore, with the influx of non-agricultural neighbors, tree fruit producers must contend with an array of new local, county and state ordinances against standard operational practices that may produce noises or chemical trespass. The Clarksville Horticulture Experiment Station is in proximity to one of Michigan's fastest growing population centers, Grand Rapids. Not unlike other areas affected by suburban sprawl and human encroachment, producers in this region are searching for alternative production strategies that mitigate line-of-sight, noise, and chemical drift. In states like Michigan where orchards are grown in close proximity to water, additional issues arise from evolving promulgation of the Endangered Species Act of 1973 and Clean Water Act of 1977 (Public Law 93–205 and Public Law 95–217) leading to an additional need for pesticide drift and orchard operation buffers, barriers and filter-strips aimed at mitigating chemical trespass, noise reduction and impacts on water and endangered species. Hedgerow barriers may play an increasingly important role in addressing some of these concerns.

To date, several commercial producers have planted hedgerow barriers in Michigan's sprawl affected production regions. Certainly, this strategy will need to be examined and evaluated over a number of years and in high pest pressure settings, yet this study suggests that hedgerows may afford some pest management advantages along with sound mitigation and chemical drift interception reported elsewhere[16].

Acknowledgements. We express our sincere appreciation to Andrea B. Coombs, Deepa Ramsinghani and Peter McGee for their excellent technical assistance and support for data collection and processing. This project was funded by GREEEN (Generating Research and Extension to meet Economic and Environmental Needs) and Gerber Products Company.

References

1 Rice, R.E. and Kirsch, P. 1990. Mating disruption of oriental fruit moth in the United States. In R.L. Ridgway, R.M. Silverstein and M.N. Inscoe (eds). Behavior-modifying Chemicals for Insect Management: Applications of Pheromones and Other Attractants. M. Dekker, New York. p. 193–211.

2 Howitt, G.H. 1993. Common Tree Fruit Pests. Michigan State University Extension, NCR 63, E. Lansing, MI.

3 Hull, L. and Krawcyzk, G. 2001. Oriental fruit moth degree day model. Penn Fruit News 81:23–36.

4 Reissig, W.H., Stanley, B.H., and Hebding, H.E. 1986. Azinphos-methyl resistance and weight-related response of obliquebanded leafroller (Lepidoptera: Tortricidae) larvae to insecticides. Journal of Economic Entomology 78:692–699.

5 Bush, M.R., Abdel-Aal, Y.A.I., and Rock, G.C. 1993. Parathion resistance and esterase activity in codling moth (Lepidoptera: Tortricidae) from North Carolina. Journal of Economic Entomology 86:660–666.

6 Chapman, K.L. and Barrett, B.A. 1997. Susceptibility of the codling moth (Lepidoptera: Tortricidae) to azinphosmethyl in Missouri. Journal of Agricultural Entomology 14:441–447.

7 Ahmad, M., Hollingworth, R.M., and Wise, J.C. 2001. Broad-spectrum insecticide resistance in obliquebanded leafroller *Choristoneura rosaceana* (Lepidoptera: Tortricidae) from Michigan. Pest Management Science 58:834–838.

8 Waldstein, D.E. and Reissig, W.H. 2000. Synergism of tebufenozide in resistant and susceptible strains of obliquebanded leafroller (Lepidoptera: Tortricidae) and resistance to new insecticides. Journal of Economic Entomology 93:1768–1772.

9 Croft, B.A. and Hoyt, S.C. 1978. Considerations for the use of pyrethroid insecticides for deciduous fruit pest control in the USA. Environmental Entomology 7:627–630.

10 Croft, B.A. 1982. Arthropod resistance to insecticides: a key to pest control failures and successes in North American apple orchards. Entomologia Experimentalis et Applicata 31:88–110.

11 Whalon, M.E. and Croft, B.A. 1982. Apple IPM (integrated pest management) in North America. Annual Review of Entomology 29:435–470.

12 Wise, C.J. and Gut, L.J. 1999. Season long broad spectrum insect control. Arthropod Management Tests 24:A33.
13 Wise, C.J. and Gut, L.J. 2000. Control of plum curculio. Arthropod Management Tests 25:A26.
14 Chandler, W.H. 1925. Conditions that affect the minimum temperature in orchards and means of avoiding injury. In W.H. Chandler (ed.). Fruit Growing. Houghton Mifflin Company, The Riverside Press, Cambridge. p. 569–584.
15 Childers, N.F. 1976. Establishing the fruit planting. In N.F. Childers (ed.). Modern Fruit Science. Horticultural Publications, Rutgers University, New Brunswick, NJ. p. 31–65.
16 Hewitt, A.J. 2001. Drift filtration by natural and artificial collectors: a literature review. Available at Web site http://www.agdrift.com/PDF_FILES/drift%20filtration.PDF.
17 Maxwell, C.W. 1968. The recapture of marked apple maggot adults in several orchards from one release point. Journal of Economic Entomology 61:1157–1159.
18 Whalon, M.E. and Croft, B.A. 1985. Dispersal of Apple Pests and Natural Enemies in Michigan. Michigan State University, Agricultural Experiment Station Research Report 467. 24 p.
19 Prokopy, R.J., Johnson, S.A., and O'Brien, M.T. 1990. Second-stage integrated management of apple arthropod pests. Entomologia Experimentalis et Applicata 54:9–19.
20 Welsh, D.B. and Grove, G. 2001. Repelled and repulsed: two-spotted spider mites react to agrochemicals. Agrochemical and Environmental News 181:14–17.
21 Whalon, M.E. and Croft, B.A. 1986. Immigration and colonization of portable apple trees by arthropod pests and their natural enemies. Crop Protection 5:376–384.
22 Larsen, K.J. and Whalon, M.E. 1988. Dispersal of *Paraphlepsius irroratus* (Say) (Homoptera: Cicadellidae) in peach and cherry orchards. Environmental Entomology 17:842–851.
23 Mowry, T.M. and Whalon, M.E. 1984. Comparisons of leafhopper species complexes in the ground cover of sprayed and unsprayed peach orchards in Michigan (Homoptera: Cicadellidae) a. The Great Lakes Entomologist 17:205–209.
24 Whalon, M.E. and Elsner, E.A. 1982. Impact of insecticides on *Illinoia pepperil* and its predators. Journal of Economic Entomology 75:356–358.
25 Bush, M.R. and Whalon, M.E. 1994. Investigating Ground Cover and Physical Barriers for Control of Pests and Augmentation of Natural Enemies on Stone Fruit. Report to the Southwest Michigan Research and Extension Center, Benton Harbor, MI.
26 Bush, M.R. and Whalon, M.E. 1995. Investigating ground cover and physical barriers for control of pests and augmentation of natural enemies on stone fruit. Report to the Southwest Michigan Research and Extension Center, Benton Harbor, MI.
27 Zar, J.H. 1984. Biostatistical Analysis. 2nd ed. Prentice-Hall, Englewood Cliffs, NJ. p. 236–238.
28 Ahmad, T.R. and Al-Gharbawi, Z.A. 1986. Effects of pheromone trap design and placement on catches of codling moth, *Cydia pomonella* males. Journal of Applied Entomology 59:52–57.
29 Howell, J.F., Schmidt, R.S., Horton, D.R., Khattak, S.U.K., and White, L.D. 1990. Codling moth: male moth activity in response to pheromone lures and pheromone-baited traps at different elevations within and between trees. Environmental Entomology 19:573–577.
30 Lawson, D.S., Reissig, W.H., Agnello, A.M., Nyrop, J.P., and Roelofs, W.L. 1996. Interference with the male-finding communication system of the obliquebanded leafroller (Lepidoptera: Tortricidae) using synthetic sex pheromones. Environmental Entomology 25:895–905.
31 Agnello, A.H., Reissig, W.H., Spangler, S.M., Charlton, R.E., and Kain, D.P. 1996. Trap response and fruit damage by obliquebanded leafroller (Lepidoptera: Tortricidae) in pheromone-treated apple orchards in New York. Environmental Entomology 25:268–282.
32 Rothschild, G.H.L. and Minsk, A.K. 1974. Time of activity of male Oriental fruit moth at pheromone sources in the field. Environmental Entomology 3:1003–1007.
33 Rothschild, G.H.L. and Minsk, A.K. 1977. Some factors influencing the performance of pheromone traps for Oriental fruit moth in Australia. Entomologia Experimentalis et Applicata 22:171–182.
34 Phillips, J.H.H. and Proctor, J.R. 1969. Studies on the fecundity and behavior of the Oriental fruit moth, *Grapholitha molesta* (Lepidoptera: Tortricidae), on the Niagara Peninsula of Ontario. Canadian Entomologist 101:1024–1033.
35 Hughes, J. and Dorn, S. 2002. Sexual differences in the flight performance of the oriental fruit moth *Cydia molesta*. Entomologia Experimentalis et Applicata 103:171–182.

Renewable Agriculture and Food Systems: 22(3); 189–203 doi:10.1017/S1742170507001731

A multi-criteria evaluation of the environmental performances of conventional, organic and integrated olive-growing systems in the south of Spain based on experts' knowledge

Carlos Parra-López[1,*], Javier Calatrava-Requena[1], and Tomás de-Haro-Giménez[2]

[1]Department of Agricultural Economics and Rural Sociology, Andalusian Institute of Agricultural Research—IFAPA, PO Box 2027 18080 Granada, Spain.
[2]Department of Agricultural Economics, Sociology and Policy, University of Cordoba, PO Box 3048 14080 Cordoba, Spain.
*Corresponding author: carparra@teleline.es

Accepted 27 September 2006 **Research Paper**

Abstract

The medium to long-term environmental performances of organic, integrated and conventional olive-growing systems in the average conditions of the south of Spain are evaluated and compared with respect to soil erosion, soil fertility, rational use of irrigation water, water contamination, atmospheric pollution and biodiversity, based on experts' knowledge. The aim of the research was to test the common implicit assumption of environmental superiority of the two alternative farming systems over the conventional system. For this purpose, the Analytic Hierarchy Process (AHP), a widely used multi-criteria decision-making tool, has been implemented. AHP enables us to deal with complex decision-making problems with multiple criteria, stakeholders and decision-makers, high uncertainty and risk, such as in the case of multi-criteria environmental comparison of alternative farming systems. Twenty experts in olive production, clustered into three groups according to their professional field of interest, were involved in the analysis. The utilization of experts' knowledge is justified when information relevant for urgent decision-making is not available, is partial or is time and resource demanding, and a holistic perspective is required. Indexes and procedures are proposed for group decision-making, to detect variation in expert opinions and differences between alternative systems' performances. Despite bias in the judgments of the groups of experts in some topics, results confirm the holistic environmental superiority of organic and integrated alternatives over the conventional olive system in Andalusia in the medium to long-term. The results represent a scientific base to justify and endorse institutional support regarding the promotion and implementation of organic and integrated olive-growing systems in the region, which are likely to result in greater social welfare.

Key words: organic agriculture, integrated farming systems, environmental assessment, multi-criteria decision-making, AHP, *Olea europaea* L.

Introduction

When environmental effects of dominant conventional/chemical farming techniques are considered, many voices from fields of science, politics and society in general have been questioning, for some time, the medium to long-term sustainability of agriculture. Examples can be found in: Green Book of the European Commission in 1985[1]; Brundtland Report[2]; Agenda 21[3]; Rio Declaration[4]; Maastricht Treaty in 1992; Amsterdam Treaty in 1997; Cork Declaration[5]; 'Mad Cow' Report; '2000 Agenda' CAP—Common Agricultural Policy—Reform (EU Reg 1251/99 to 1268/99); Mid-Term 2003 CAP Reform (EU Reg 1782/2003)[6]; among others.

In fact, conventional farming practices are causing environmental damage, which is sometimes difficult to quantify and might have irreversible consequences. Aggressive actions include the following. (1) *Intensive soil*

© 2007 Cambridge University Press

management practices, related to losses of soil and therefore fertility. In southern Spanish olive groves, losses are estimated at around 80×10^3 kg ha^{-1}yr^{-1}, much higher than the average rate of soil formation[7]. (2) *High energy consumption* of primarily fossil fuels both directly, by farming activities, or indirectly by fertilizer industries. It has been estimated that fertilizer production consumes approximately 24% of the total energy requirement of Spanish agriculture[8]. (3) *Prevalence of single-crop farming* that eliminates genetic variety of plants and increases the appearance of pests and diseases and the selective exhaustion of certain soil nutrients. (4) *Massive use of chemical fertilizers* that causes freshwater contamination in developed countries owing to the accumulation of nitrates in underground waters, and phosphates in surface waters. (5) *Great use of phytosanitary products and chemical herbicides*, which usually take a long time to break down. We know hardly anything about their effect on human health. When their levels build up in the soil and continental waters, they have devastating effects on soil microorganisms, which are the basis of soil fertility, and on higher organisms by eliminating the natural enemies of pest species. (6) *Overexploitation of underground waters*, which together with excessive use of chemical substances, leads to salinization of water supplies. Moreover, the build-up of salt and heavy metals in the soil can deplete soil fertility and favor the advance of desertification. (7) *Stubble burning*, that leads to a significant elimination of soil organic matter, which gives rise to a substantial loss of fertility and, since it leaves the soil bare, leads to higher levels of erosion. (8) *Intensive livestock raising methods* using hormones, medicines and unnatural food for animals, that give rise to serious public health problems, such as mad cow disease.

Social awareness of these environmental problems, along with an increasing social demand on quality of food and sustainability of agriculture, among other factors, has given rise to the diffusion throughout 20th and 21st centuries of different alternative farming methods. Among these alternatives, two particularly stand out for their growing level of implementation in the European Union (EU) in general, and in Spain in particular: organic agriculture [Council Regulation (EEC) No 2092/91, in force in the EU with few minor modifications] and integrated farming systems (for which no specific regulation exists at EU level, but which is regulated within Spain by Real Decreto 1201/2002). Andalusia, located in the south of Spain, is the world's leading olive-growing region. In this zone, although the presence of these farming methods is still not very important (in 2000, 1.50% of the total olive area was organic and 1.07% was integrated), they have been increasingly put into practice over the past years[9].

In the diffusion process of these alternative farming systems, it is implicitly or explicitly assumed that they are more valuable from an environmental point of view than the conventional system and therefore their implementation is a desirable objective which will have a beneficial effect on social welfare in any socio-economic, environmental, etc., context and any cultivation. Although the number of partial studies, usually focusing on just one or few criteria, about the impact on the environment of conventional versus alternative farming techniques is increasing, little information is available from a multi-criteria and holistic perspective, especially for the case of olive cultivation in Andalusia. Thus, one of the main objectives of this paper is to provide a quantitative assessment and comparison of the relative environmental performances of the three farming systems—conventional, organic and integrated—from a multi-criteria perspective, in the average yield, climatic, environmental, etc., conditions of olive cultivation in Andalusia. The final aim of this comparison is to test the accuracy of the hypothesis stating that the two alternative farming methods are environmentally superior to the technology they hope to replace. Confirmation of this hypothesis would provide a scientific base to justify and endorse institutional support regarding the promotion and implementation of these farming systems in this region and cultivation.

Methodology: The Analytic Hierarchy Process (AHP)

In order to carry out this research, the AHP[10–12] has been implemented. This is a multi-criteria decision-making (MCDM) technique widely implemented in many scientific fields (see http://www.expertchoice.com). However, its application in *environmental assessment of agricultural systems* has not been found in the international literature, although it could be a very suitable and powerful tool for this purpose, as we will try to show. AHP has been used in the context of related topics such as *evaluation of the sustainability of land use systems*. In this field, it was applied beside Compromising Programming (CP) for a case study on an irrigation project in Thailand[13]. Another study related to forest concessions, uses ranking, rating and pairwise comparisons, the latter being based on AHP[14]. It has also been empirically implemented in *environmental assessment and evaluation* in other fields (http://www.expertchoice.com): in regional seas management; as part of a methodology for Environmental Impact Evaluations (EIEs) of big projects such as highways, classification and selection of projects in a de-pollution plan for ports; and to evaluate US environmental policies. AHP has also been *integrated within a greater decision-making framework* for forest planning[15]; it has been proposed for *compiling an inventory and monitoring* the management of Natural Parks in the USA[16]; and it has been used to *evaluate different mountain ecosystems*, including socio-economic and environmental criteria in the analysis[17]. Moreover, it has been applied to *compare the social value* of the environment, agriculture and certain attributes of preserved land in Delaware (USA)[18]. In Spain, AHP has been implemented to *evaluate different protection figures* of Natural Areas[19], and to assess *natural ecosystems* based on expert judgements[20]. Other Spanish studies have applied AHP to *environmental selection and assessment* mainly in basin management[21–23].

AHP can be placed within the MCDM framework. More specifically, AHP along with Multi-Attribute Utility Theory (MAUT) and Outranking Methods are the main discrete MCDM methods[24], applicable when the nature of alternatives is non-continuous. Brunner and Starkl[25] presented a critical survey and comparison of these and other decision tools. The choice of a particular method for environmental/economic decision-making must be guided by a trade-off between comprehensiveness and objectivity[13]. AHP provides a good compromise between these two targets. In effect, the *comprehensiveness* of AHP is one of its major strengths. This is an analytical tool, supported by simple mathematics. It enables people to rank tangible and intangible factors explicitly for the purpose of resolving conflict or setting priorities[11]. A main aim of AHP is to be a simple way to help ordinary people make complex decisions[26]. Moreover, Expert Choice software[27] provides a user-friendly program, which facilitates its empirical implementation. On the other hand, AHP increases the transparency and *objectivity* of the decision-making process because when there are various involved agents, they must explicitly state their preferences, thus facilitating the detection of controversial items and increasing agreement in the process. Moreover, decision-makers are continually learning in the decision-making process proposed by AHP, it being possible and advantageous to feed-back subsequent information into the initial phases of the process[12,26]. As an extra added value, AHP enables the incorporation of qualitative, subjective and intangible information, in complex decision-making problems and situations with multiple criteria, stakeholders and decision-makers, high uncertainty (lack of information) and high risk (what is at stake). These properties are useful in environmental assessment and choice, as in the case of the holistic environmental evaluation of farming systems, and make AHP a potentially useful tool in this field. AHP suggests an analysis and synthesis process for decision-making that consists of a series of steps or phases. In the present research paper, we complement these steps with an extension to measure agreement and similarity of the decision-makers' opinions, as shown in the next sections. The complete extended AHP process, explained below, is schematized in Figure 1.

Analysis of the problem

The first step of AHP is to break the problem down into smaller parts, that is, its analysis, and to structure it by means of the construction of a decision hierarchy or model. First, it is necessary to define the main objective or goal. Usually the achievement of this main objective involves satisfying a set of more specific objectives and sub-objectives at lower levels of the model (Fig. 1, 'Analysis of the problem' section). In the literature, criteria and objectives are distinguished. A criterion is a rule to discern one thing from another. An objective is a criterion with an established improvement direction, e.g., a criterion in the selection of a car could be 'petrol consumption' and an objective of the decision-maker could be 'low petrol consumption'. The alternatives will be ranked according to their respective performances with respect to the goal which depends on the satisfaction of the more specific objectives. It is very important to include just relevant and uncorrelated objectives. Moreover, according to the 'axiom of independence of elements' of AHP[26], the priorities or importance of the elements (objectives, sub-objectives and alternatives) in the upper levels must not be dependent on the lower level elements. If these conditions of non-correlation and independence cannot be guaranteed in a particular application, a more sophisticated elaboration of the AHP, the so-called Analytic Network Process (ANP)[28], which surpasses the object of this paper, could be implemented.

Assessment of nodes

The next step is to assess for each objective or, in general terms, each node of the hierarchy tree, the local priorities or weights (ω_L) of the subnodes or alternatives that depend on it, in terms of importance, preference or likelihood (Fig. 1, 'Assessment of nodes' section). In AHP, the standardization of local priorities in each node is usually imposed, that is, $0 \leqslant \omega_{L(i)} \leqslant 1$, and $\sum_{i=1}^{n} \omega_{L(i)} = 1$, where $\omega_{L(i)}$ is the local weight of an i sub-node or alternative with respect to its parent node, and n is the number of sub-nodes or alternatives depending on the parent node. AHP suggests the calculation of these priorities on the basis of ratios between them ($\omega_{L(i)}/\omega_{L(j)}$). These ratios are usually obtained for every node of the hierarchy from experts or decision-makers' judgments about the relative importance, stated by simple *pairwise comparisons*, of the performances of the sub-nodes or alternatives depending on them. AHP enables the use of three different comparison scales[11]: (1) *numerical*: e.g., sub-node i is 2.5 times more important than node j with respect to their parent node, that is, $\omega_{L(i)}/\omega_{L(j)} = 2.5$; (2) *graphical*, on the basis of the length of two bars that represent the relative importance of the two sub-nodes or alternatives; or (3) *verbal*, in a scale ranging from equal ($\omega_{L(i)}/\omega_{L(j)} = 1$) to extreme preference ($\omega_{L(i)}/\omega_{L(j)} = 9$) of an element against the other. The 'homogeneity axiom' of AHP[26] states that the elements being compared should not differ too much, since errors in judgments tend to be larger. Based on these pairwise comparisons, a comparison matrix ($\hat{A}$) for each node can be constructed

$$\hat{A} = \begin{pmatrix} 1 & \omega_{L(1)}/\omega_{L(2)} & \omega_{L(1)}/\omega_{L(3)} & \cdots & \omega_{L(1)}/\omega_{L(n)} \\ & 1 & \omega_{L(2)}/\omega_{L(3)} & \cdots & \omega_{L(2)}/\omega_{L(n)} \\ & & 1 & \cdots & \omega_{L(3)}/\omega_{L(n)} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \text{Inverse} & & & \cdots & 1 \\ \text{elements} & & & & \end{pmatrix} \quad (1)$$

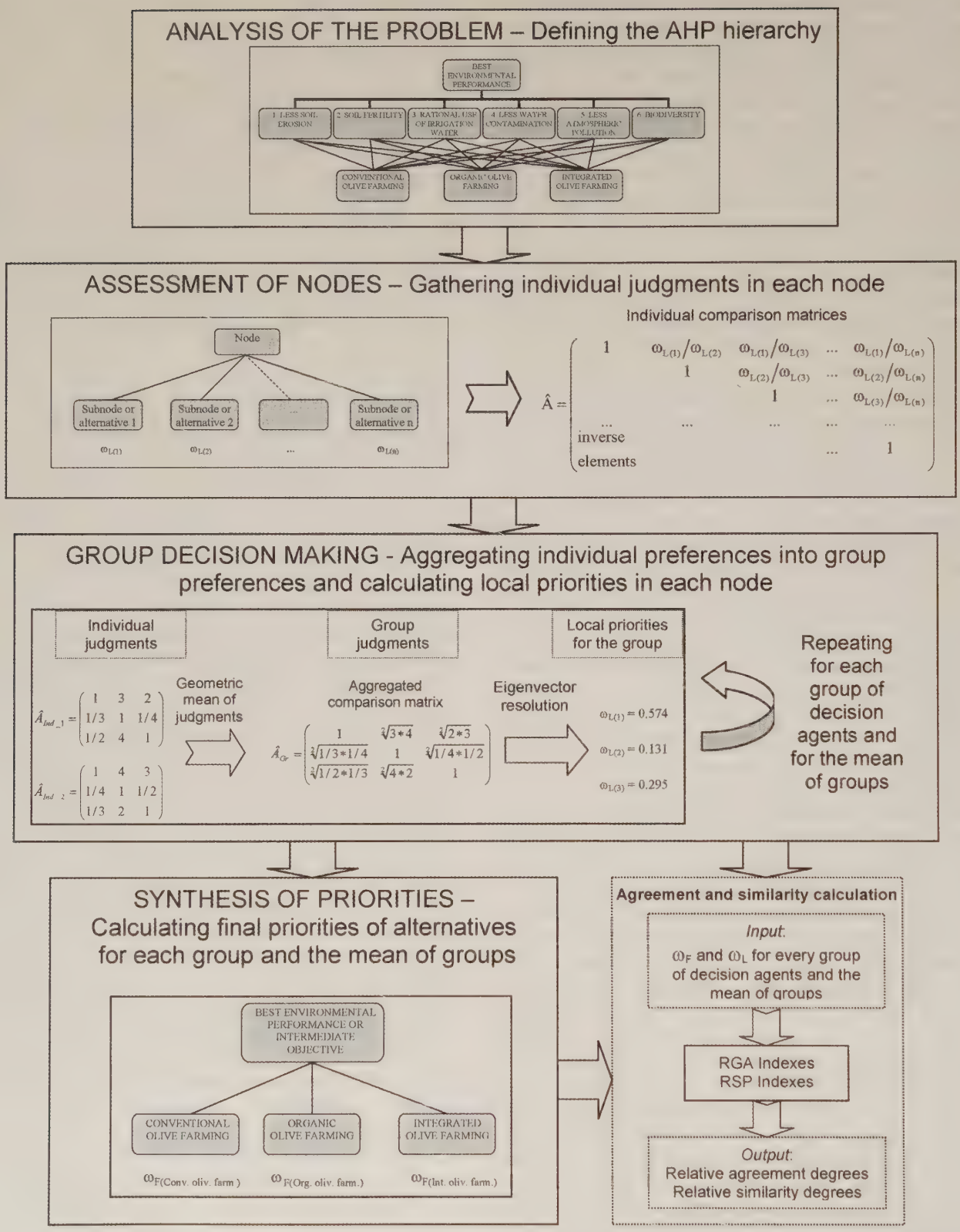

ANALYSIS OF THE PROBLEM – Defining the AHP hierarchy
BEST ENVIRONMENTAL PERFORMANCE
1. LESS SOIL EROSION
2. SOIL FERTILITY
3. RATIONAL USE OF IRRIGATION WATER
4. LESS WATER CONTAMINATION
5. LESS ATMOSPHERIC POLLUTION
6. BIODIVERSITY
CONVENTIONAL OLIVE FARMING
ORGANIC OLIVE FARMING
INTEGRATED OLIVE FARMING
ASSESSMENT OF NODES – Gathering individual judgments in each node
Node
Subnode or alternative 1
Subnode or alternative 2
Subnode or alternative n
Individual comparison matrices
inverse elements
GROUP DECISION MAKING - Aggregating individual preferences into group preferences and calculating local priorities in each node
Individual judgments
Group judgments
Local priorities for the group
Geometric mean of judgments
Aggregated comparison matrix
Eigenvector resolution
ω_L(1) = 0.574
ω_L(2) = 0.131
ω_L(3) = 0.295
Repeating for each group of decision agents and for the mean of groups
SYNTHESIS OF PRIORITIES – Calculating final priorities of alternatives for each group and the mean of groups
BEST ENVIRONMENTAL PERFORMANCE OR INTERMEDIATE OBJECTIVE
CONVENTIONAL OLIVE FARMING
ORGANIC OLIVE FARMING
INTEGRATED OLIVE FARMING
ω_F(Conv. oliv. farm.)
ω_F(Org. oliv. farm.)
ω_F(Int. oliv. farm.)
Agreement and similarity calculation
Input:
ω_F and ω_L for every group of decision agents and the mean of groups
RGA Indexes
RSP Indexes
Output:
Relative agreement degrees
Relative similarity degrees

Figure 1. Extended-AHP framework.

$\hat{A}$ is a positive reciprocal matrix with some important properties: it is squared ($n \times n$ order, with n = number of sub-nodes or alternatives depending on the analyzed node), each element in the lower left triangle of the matrix is the inverse of its counterpart in the upper right triangle (that is, $a_{i,j} = 1/a_{j,i}$, $\forall i,j,i,j = 1, 2, \ldots, n$, being $a_{i,j} = \omega_{L(i)}/\omega_{L(j)}$; this property is known as the 'reciprocal axiom of AHP[26]), and with elements in the diagonal equal to 1 ($a_{i,j} = 1$, $\forall i$). It can be demonstrated that local priorities of the components ($\omega_{L(i)}$) can be calculated by solving for the eigenvector of the system of equations

$$\hat{A} * \varpi_L = \lambda * \varpi_L, \tag{2}$$

where ω_L is the vector $(\omega_{L(1)}, \omega_{L(2)}, \ldots \omega_{L(n)})^T$ and λ is the maximum eigenvalue. The consistency of decision-makers' judgments can also be calculated as the difference $\lambda - n$ since always $\lambda \geqslant n$. An in depth explanation of the mathematical fundamentals of AHP can be found, e.g., in Saaty[12].

Group decision-making

When decision-making involves the participation of different decision agents, in the literature about AHP the *Aggregation of Individual Judgments* (*AIJ*) method, among others, has been proposed to aggregate individual judgments into group judgments[29,30]. Once we have the individual comparison matrices of every decision agent in a particular node of the hierarchy ($\hat{A}_{Ind\_1}, \hat{A}_{Ind\_2}, \ldots, \hat{A}_{Ind\_N}$; N being the number of individuals pertaining to the group), it is possible to calculate for this node an aggregated comparison matrix for the group ($\hat{A}_g$) (Fig. 1, 'Group decision-making' section). There are different proposals of aggregation of the judgments functions although the most widespread one is the *geometric mean* because it satisfies some advisable properties such as unanimity, homogeneity and reciprocity[31]. The elements of the group comparison matrix would be: $(a_{i,j})_g = \sqrt[N]{\prod_{n=1}^{N} (a_{i,j})_{Ind\_n}}$, where $(a_{i,j})_{Ind\_n}$ is the judgment of the individual n, which belongs to the group, about the relative importance of $\omega_{L(i)}$ versus $\omega_{L(j)}$. Once $\hat{A}_g$ is calculated for the node, it is possible to obtain the local priorities of sub-nodes or alternatives for the group, applying Equation (2).

In group decision-making, conflicts among judgments of individuals or groups of individuals often arise. In the AHP literature, the homogeneity of the group is usually assumed, that is, the non-variance of the judgments among decision-makers[32]. However, some authors have questioned this assumption[33–38]. Here, we propose some indexes and procedures to calculate the *relative consensus* among different groups of agents involved in the decision-making process and to measure the *relative similarity of the performances* of the alternatives or sub-objectives according to the mean opinion of all the groups. In short, these indexes are

1. *Relative Global Agreement Index* (RGA Index) among all groups of decision agents in a particular node: it is a measure of the deviation of the opinions of all the groups of decision agents with respect to the mean opinion. The greater the RGA Index in a node, the greater the consensus among opinions of all groups in the node would be. Mathematically, RGA has been defined as:

$$RGA = \frac{1}{\sum_{\forall g} \left\{ \frac{\left[\sum_{i=1}^{n} \frac{\left(\left| \omega_{L(i),g} - \omega_{L(i),m} \right| \right)}{\omega_{L(i),m}} \right]}{n} \right\}}{G} \tag{3}$$

   where G is the number of decision groups, g is a particular decision group, $\omega_{L(i),g}$ is the mean local priority of the sub-node or alternative 'i' with respect to its parent node for the 'g' group of agents, $\omega_{L(i),m}$ is the mean local priority of the sub-node or alternative 'i' with respect to its parent node for the G groups of agents and n is the number of child sub-nodes or alternatives of the analyzed node.

2. *Relative Similarity of Performance Index* (RSP Index) in a node: it is a measure of the deviation of the mean opinion of all the groups of decision agents with respect to the theoretical homogeneous priorities, such as in the case that all the sub-nodes or alternatives weigh the same. It enables us to determine whether the performances are similar or not, according to the mean opinion of all the groups. The greater the RSP Index in a node, the more similar to each other the performances of the subnodes or alternatives in the node according to the mean opinion of all the decision groups. Mathematically, RSP is defined as

$$RSP = \frac{1}{\frac{\left[\sum_{i=1}^{n} \frac{\left(\left| \omega_{L(i),m} - \omega_{h(n)} \right| \right)}{\omega_{h(n)}} \right]}{n}}, \tag{4}$$

   where $\omega_{h(n)} = 1/n$, $\omega_{h(n)}$ being the hypothetical totally uniform priorities in the node, e.g., if the number of sub-nodes or alternatives depending on the node is 4 ($n = 4$) then $\omega_{h(4)}$ would be $1/4 = 0.250$.

Values of both indexes are real positive numbers. However, we are more interested in the ranking of these indexes than in the values themselves. On the basis of the order of the indexes in all the nodes of a hierarchy, including aforesaid local priorities and final priorities which will be defined in the next section, it is possible to segment the relative degrees of agreement and similarity among the decision-agents' priorities in the complete hierarchy (Fig. 1, 'Agreement and similarity calculation' section). For example, RGA and RSP indexes can be clustered, respectively, in three sets with approximately the same number of nodes within: the first division would be nodes with the *lower* relative agreement (similarity) degree, the second with the *medium* relative agreement (similarity) degree and the third with the *higher* relative agreement (similarity) degree. It is very important to underline that the

segmentations are exclusive and different for each AHP model and they are just used to cluster agreement and similarity in relative terms, to locate the more and less controversial elements in each particular AHP hierarchy. In accordance with the Procedural Rationality postulates[22], we are more interested in the improvement of the decision-making process in a particular problem by detecting the more controversial items in 'relative' terms than in the definition of some 'absolute' indexes which could be significant for some decision problems but not for others.

Synthesis of priorities

Once all nodes of the hierarchy have been assessed and, if it is the case, individual judgments have been properly aggregated, and the local priorities have been calculated, the alternatives must be prioritized, that is ranked, on the basis of their relative performances with respect to the goal or any intermediate node of the decision hierarchy. For this prioritization to take place, it is necessary to calculate the *final priorities of the alternatives* (ω_F) with respect to the goal or any intermediate node (Fig. 1, 'Synthesis of properties' section). It is a question of calculating the weights of the alternatives with respect to the overall or the intermediate node on the basis of the local priorities of all the sub-objectives and alternatives depending on it, by weighted addition from the bottom to the upper level of the hierarchy (see, e.g., Forman and Selly[26]). Once the final priorities in a node are obtained, it is possible to calculate the RGA and RSP Indexes for these final priorities in a similar way as for local priorities, by just substituting local priorities (ω_L) by final priorities (ω_F) in Equations (3) and (4). The RGA and RSP for final priorities in all the nodes of the model must be included in the definition of sets of agreement and similarity, as we suggested in the previous section.

The Case Study: Alternative Olive Systems in Andalusia, Spain

Andalusia is a region in the south of Spain placed between a latitude of 36° and 38° 44′ north and has a typical Mediterranean climate. Average annual temperatures range between 12 and 21°C, depending on the specific zone, with mild winters and very hot summers. The mean rainfall is 595 mm yr^{-1}, although its spatial and temporal variability is very strong. According to the FAO Soil Classification (and equivalent US soil taxonomy system), around 33% of the Andalusian soil surface is Cambisol (Inceptisol), soil with incipient changes in color, structure, etc., due to meteorological factors. Twenty percent is Regosol (Ortherent, Psamment), soil with a thin effective depth, developed under unconsolidated material; it is typical of mountain regions. Thirteen percent is Luvisol (Alfisol), soil with a medium-high base saturation percentage in the argillaceous stratum; it is typical of basin terraces. The total surface area of this region is 8 759 700 ha, with 4 036 015 ha dedicated to agriculture, of which 1 503 276 ha are devoted to olive cultivation. Annual average olive yield is 3806 kg of olives ha^{-1}, according to Junta de Andalucía[39]. The olive cultivation in Andalusia represents around 60% of the Spanish olive surface area and 80% of the Spanish olive production. The past few decades have witnessed fundamental changes in olive farming[40]. The number of olive farmers has decreased, their average age has increased and the work is becoming more specialized. Production is sometimes excessive. Moreover, new pests appear and old pests are more numerous and have built up resistance to control methods. A drop in beneficial insect fauna has occurred. In addition, environmental pollution, including atmosphere, soil and surface and underground waters, has increased, leading to possible residual traces in the olives. Consequently, a field study[41] has demonstrated the low rationality of the conventional practices actually implemented in the olives groves of the south of Spain.

In our application, the goal, or overall objective, is to determine which of the three analyzed alternatives (conventional, organic or integrated olive-growing systems), has a greater environmental value for society in the average yield, climatic, environmental, etc. conditions of Andalusia, and therefore is more desirable in the medium to long-term. This overall objective has been divided into different sub-objectives, which have been defined on the basis of different information and sources aiming to include the more relevant issues: (1) EU CAP and national regulations on agriculture; (2) experts' advise from a pre-test of the model to five interviewees; and (3) multiple references in the literature related to sustainable agriculture, environmentally friendly agricultural practices and responsible management of natural resources. The decision hierarchy is shown in Figure 2 and the meaning of the sub-objectives is in short:

1. *Less soil erosion*: erosion is a major agri-environmental problem in Spain. Increasing inputs of, for instance, fertilizers and seeds are used in an attempt to mitigate the negative effects of erosion on agronomic yield. Erosion is related with the advance of desertification and abandonment of agriculture.
2. *Soil fertility*: in addition to prevention of soil loss, it is also important that the agronomic quality of the soil is maximized. This quality depends on the structure of the soil and the low levels of pollution/contamination, among other factors.
3. *Rational use of irrigation water*: refers to the efficient use of irrigation water, which is related to the timing of irrigation, and quantity and quality of water to apply. Scarcity of water is an endemic problem of the region.
4. *Less water contamination*: we aim to assess the contamination levels of underground and surface waters caused by the application of inputs during farming (nitrates, manures, pesticides, etc.).
5. *Less atmospheric pollution*: refers to pollution associated with farming, including pollution caused by manufacturing of inputs.

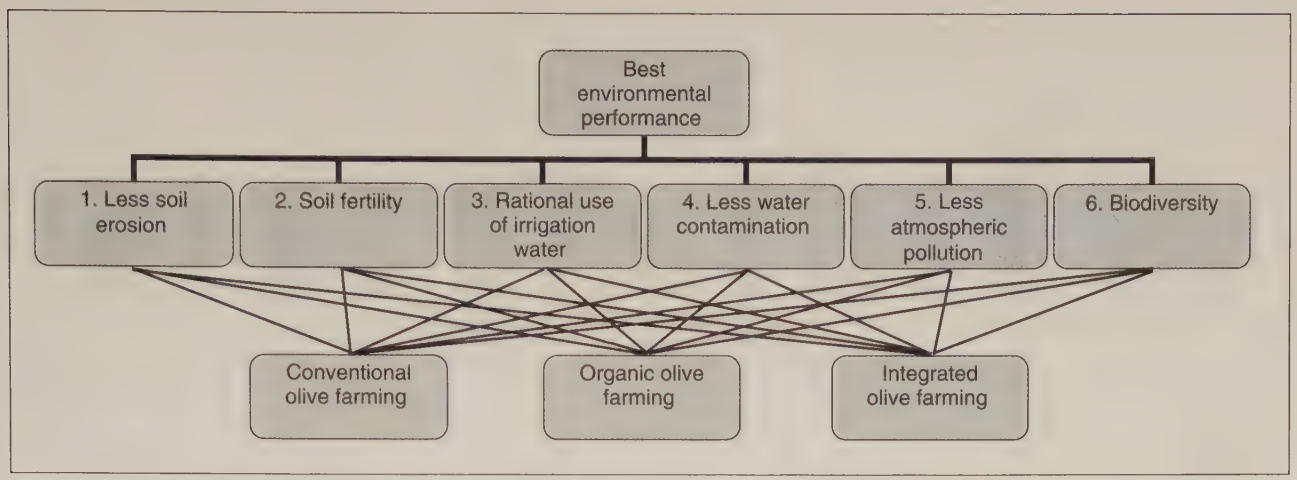


Figure 2. Proposed environmental AHP hierarchy.

6. *Biodiversity*: can be measured as the number and variety of different living beings present. It refers to the genetic diversity of olive trees, that is, the maintenance of native varieties, as well as wildlife, micro fauna, beneficial fauna, domestic animals and wild flora.

In our model, better performance of the farming systems is related to an increase of soil fertility, rational use of irrigation water and biodiversity and to a reduction of soil erosion, water contamination and atmospheric pollution.

In order to assess the nodes of the hierarchy, experts' knowledge has been used because written information, in general, and 'hard data' (e.g., data from scientific instruments), in particular, about the environmental performances of the three analyzed olive systems in Andalusia are usually not available, are partial or are expensive to obtain, both in time and resources. Moreover, analyzed criteria here are of a complex and scientific nature. Experts, if carefully selected, have in mind information that can be characterized as quantitative and qualitative, tangible and intangible, objective and subjective. Methods such as AHP enable the capture and synthesise of this information. Moreover, information can be gathered that is targeted for the problem at hand, fitting the specific criteria defined by the decision-makers or researchers, and within a reasonable time frame. The validity of AHP is strongly founded in practice and results usually corroborate those obtained with other methods that are more time and resource consuming[26]. AHP tests were conducted individually on a multi-disciplinary set of 20 experts in the three analyzed olive-growing systems, based on in-depth face-to-face interviews. Experts were prestigious scientists mainly from universities and Agricultural Research Centers of Andalusia. In any case, they were asked about the better environmental options for society as a whole in the medium to long-term and in the average conditions of the olive groves in Andalusia, and they were urged to avoid personal opinions.

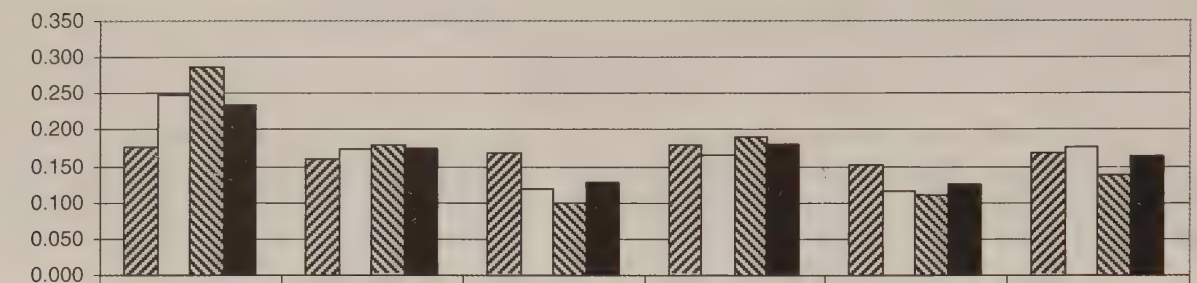
The 20 interviewed experts were clustered into three groups or types—organic, integrated and conventional—according to their professional relationship closer to a particular growing technique. The objective was to test the hypothesis that opinions of experts are related to their professional field of interest, although they were urged towards objectivity, and to isolate this potential bias due to a subjective component of the judgments of the experts. The reason not to use individual judgments of each expert is that individuals are usually, single-discipline oriented, that is, specialized in some issues, and just respond to the nodes of the model to which they have reliable knowledge. Our main objective was to have judgments of at least three experts in all the nodes of the hierarchy for each type of expert, to improve reliability of results. Finally eight conventional, four organic and eight integrated olive farming experts were interviewed. Judgments of *each group* of decision agents (type of experts) have been aggregated using the geometric mean method. Moreover, the *mean opinion of the three types of experts* has been calculated using the geometric mean of the previously mentioned judgments of the three groups of experts.

Results

Relative importance of the sub-criteria

In Figure 3, local priority of each environmental sub-criterion according to the different types of experts and the mean of the three types is shown. On the other hand, Table 1 (columns under 'Local priorities of nodes') includes these local priorities but just for the mean of the three types of interviewees (column 1), the agreement among experts on each topic (columns 5 and 6) and the similarity degree of the mean priorities (columns 9 and 10).

Priorities assigned by the organic experts usually fell in between those of the conventional and integrated ones (Figure 3). For instance, *less soil erosion* was the most important objective for the integrated group ($\omega_L = 0.287$), whereas the conventional experts regarded it to be much less important ($\omega_L = 0.176$), and the organic experts ranked its importance between these two levels ($\omega_L = 0.249$). This pattern was also found for the sub-objective *rational use of irrigation water*, but reversed: the conventional group ranked it very highly, whereas it was not considered very



	1. Less soil erosion	2. Soil fertility	3. Rational use of Irrigation water	4. Less water contamination	5. Less atmospheric pollution	6. Biodiversity
ConExp	0.176	0.159	0.167	0.179	0.151	0.168
OrgExp	0.249	0.174	0.118	0.165	0.117	0.177
IntExp	0.287	0.179	0.100	0.189	0.109	0.137
Mean	0.234	0.173	0.127	0.179	0.125	0.162

Figure 3. Relative importance of the environmental sub-criteria according to the different groups of experts and the mean opinion of the three groups of experts. ConExp = Conventional experts; OrgExp = Organic experts; IntExp = Integrated experts; Mean = Mean of the three groups.

important by the integrated experts, and the organic group placed its importance in the middle of the two former opinions. The most important sub-objectives for the conventional group were *less water contamination* and *less soil erosion*; for the integrated experts, *less soil erosion* and *less water contamination*; and finally for the organic experts, *less soil erosion* and *biodiversity*.

Moreover, the mean opinion of the three groups indicated that the environmental sub-objectives have not received very different weights in relative terms in comparison with all the nodes of the AHP model (medium relative similarity degree, RSP = 5.78, as shown in Table 1, columns 9 and10). According to the mean opinion of the three groups, the importance of the environmental sub-objectives (Table 1, column 1) in decreasing order was: (1) less soil erosion, $\omega_L = 0.234$; (2) less water contamination, $\omega_L = 0.179$; (3) soil fertility, $\omega_L = 0.173$; (4) biodiversity, $\omega_L = 0.162$; (5) rational use of irrigation water, $\omega_L = 0.127$; and (6) less atmospheric pollution, $\omega_L = 0.125$. The major importance of erosion is in agreement with the statement of Spanish regulations on agri-environmental funding (e.g. 'Real Decreto 4/2001'). The relative agreement degree about the relative importance of these sub-criteria among the three groups of experts is medium in relative terms (RGA = 8.70, as shown in Table 1, columns 5 and 6).

Performances of the farming systems in the sub-criteria

Performances of the three farming alternatives in the different environmental sub-objectives, according to the mean of the three types of experts, as well as the agreement and similarity indicators for them, are shown in Table 1 (columns under 'Final priorities of alternatives': 2–4, 7, 8, 11 and 12). Moreover, for an easier interpretation of the results, Figure 4 has been drawn. As can be seen in this figure, for all the environmental sub-objectives, the conventional olive grove was rated with the poorest performance. On the contrary, the organic alternative represented the best option for all the issues except for *less soil erosion*, where it was outperformed by the integrated olive system. In the literature contradictory evidence has been found regarding the erosion issue. In one study[42], organic farming performed even worse than conventional methods, whereas in other studies[43,44], the later[44] focusing on a marginal zone of olive in Andalusia, the organic alternative performs better with respect to this topic than the conventional one, thus supporting our findings.

Previous data refer to the mean opinion of the three types of experts. If we descend to compare the assessments among groups of experts, it is possible to detect differences in relative agreement among them (Table 1, columns 7 and 8). Thus, the items with the lowest relative agreement degree are *soil fertility* (RGA Index = 4.59), *soil erosion* (6.86) and *water contamination* (8.26).

Overall environmental performances of the farming systems

The environmental performances of the three olive-growing systems according to the mean of the three types of experts are shown in Table 1 (columns 2–4, row 'Overall environmental performance'). From the mean opinion of the experts, we can conclude that the organic olive grove is globally superior ($\omega_F = 0.386$), followed by the integrated system ($\omega_F = 0.352$) and finally conventional olive farming ($\omega_F = 0.262$). Thus, we can say that for average conditions of Andalusia, the values of environmental externalities associated with the organic and integrated olive-growing systems are, respectively, 47% [(0.386 − 0.262)/0.262] and 34% [(0.352 − 0.262)/0.262] higher than for the conventional system. These figures could be an approximation to the true environmental value of these olive-farming systems for society as a whole and could serve as a guide to estimate fair levels of compensation that society owes olive-farmers

Table 1. Priorities, agreement and similarity indicators.

Nodes of the AHP model	Local priorities of nodes[1] (ω_L)	Final priorities of alternatives[1] (ω_F)			Agreement among experts				Similarity of performance			
					Local priorities of nodes		Final priorities of alternatives		Local priorities of nodes		Final priorities of alternatives	
Goal Sub-objectives	Goal Sub-obj.	Convent. olive farming	Organic olive farming	Integrated olive farming	RGA Index	Relative agreement degree	RGA Index	Relative agreement degree	RSP Index	Relative similarity degree	RSP Index	Relative similarity degree
(Column number)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Overall environmental performance	1.000	0.262	0.386	0.352	8.70	••	8.80	••	5.78	••	7.01	••
1. Less soil erosion	0.234	0.267	0.334	0.399	n/a	n/a	6.86	•	n/a	n/a	7.54	••
2. Soil fertility	0.173	0.287	0.367	0.346	n/a	n/a	4.59	•	n/a	n/a	10.91	•••
3. Rational use of irrig. water	0.127	0.287	0.367	0.346	n/a	n/a	8.70	••	n/a	n/a	10.79	•••
4. Less water contamination	0.179	0.237	0.429	0.334	n/a	n/a	8.26	•	n/a	n/a	5.19	•
5. Less atmosp. pollution	0.125	0.252	0.421	0.327	n/a	n/a	10.53	•••	n/a	n/a	5.70	•
6. Biodiversity	0.162	0.262	0.386	0.352	n/a	n/a	12.28	•••	n/a	n/a	5.61	•

[1] According to the mean opinion of the three types of experts.

••• = Higher; •• = Medium; • = Lower; n/a = Not applicable because there are no sub-nodes depending on this node.

Note: Sets of nodes according to (a) RGA indexes: (lower relative agreement degree: 4.59, 6.86, 8.26); (medium: 8.70, 8.70, 8.80); (higher: 10.53, 12.28). (b) RSP indexes: (lower relative similarity degree: 5.19, 5.61, 5.70); (medium: 5.78, 7.01, 7.54); (higher: 10.79, 10.91).

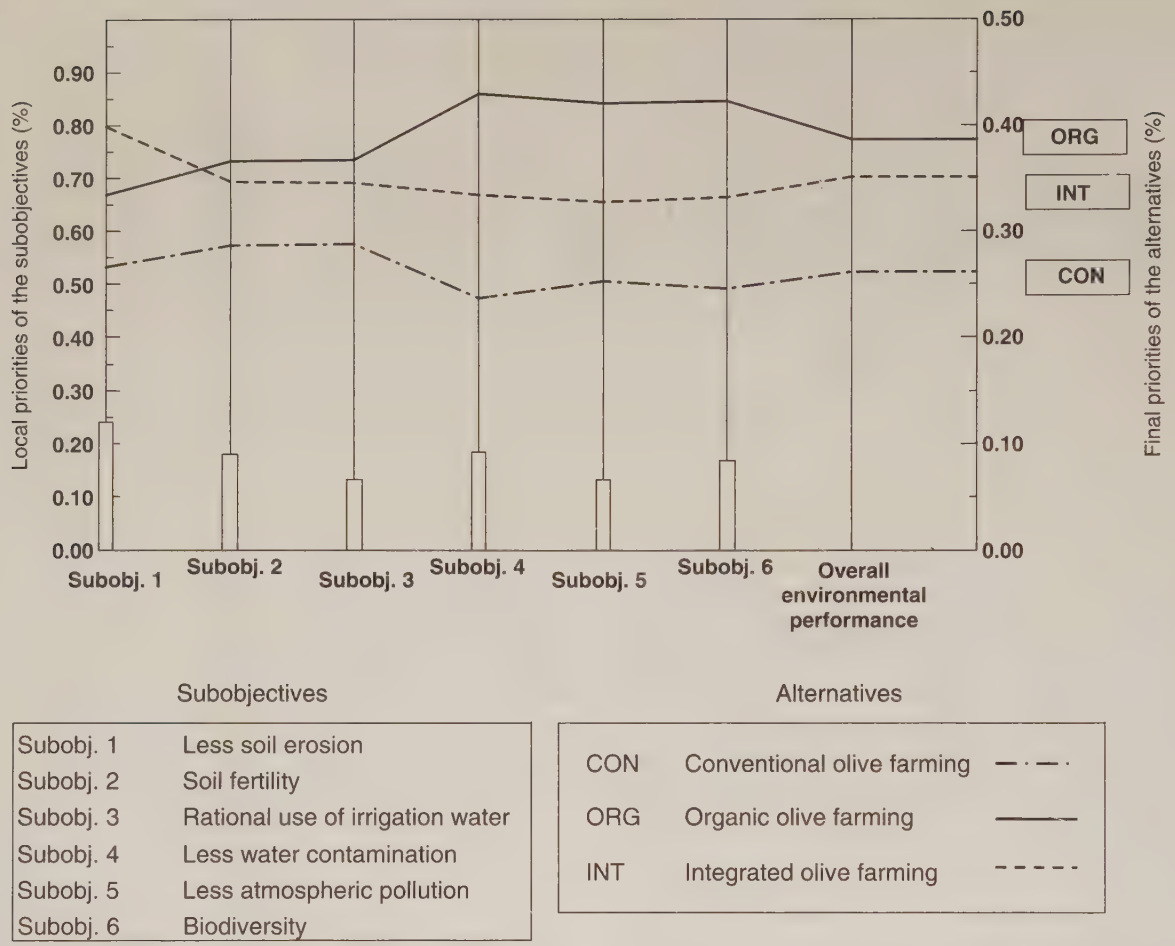
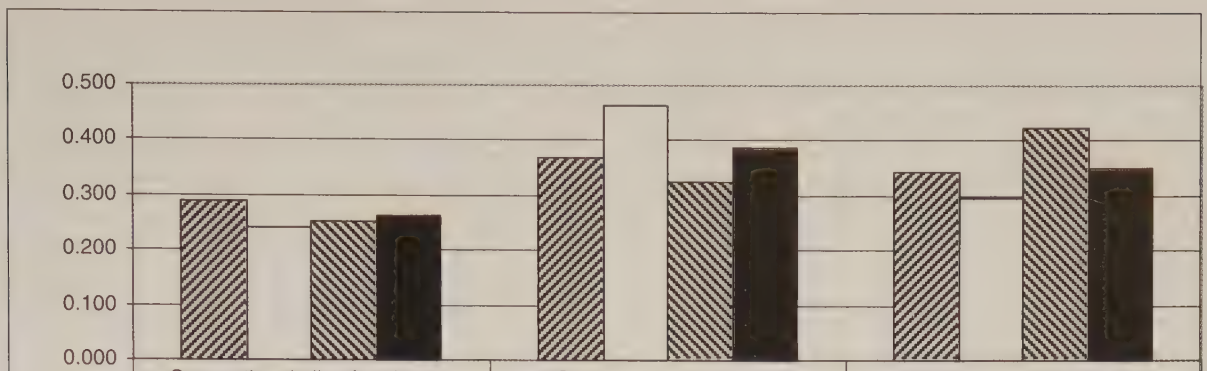


Figure 4. Environmental performances of the three farming alternatives at the goal and sub-criteria according to the mean opinion of the three types of experts. Note: Local weights of the sub-criteria are represented by the vertical bars above the name of the sub-criteria, according to the left hand side scale. The final priorities of the alternatives with respect to every sub-objective are represented by the dashed lines at the top on the vertical of every sub-objective, according to the right hand side scale. The overall priorities of the alternatives are shown on the right, according to the right scale.

who cultivate these two alternative forms of farming, e.g., via environmental subsidies, in the context of CAP cross-compliance, and through market extra prices. It provides a scientific basis to the remark: 'exponents of organic farming are arguing that support for organic farming should include maintenance rather than simply conversion payments and point to the wider benefits they believe this system provides in terms of biodiversity, . . ., and environmental management'[45]. Moreover, results show that, as for the overall performance of the three farming systems, there is a medium relative agreement degree among experts (RGA = 8.80) (Table 1, columns 7 and 8, row 'Overall environmental performance').

Although the agreement degree was not low, the non-complete agreement indicated that the average opinion was not wholly accepted by all experts. Results suggest that judgments of the experts depend on which alternative they are more related to. In Figure 5, the overall relative performances of the farming systems according to each type of expert are shown. It can be observed that the organic experts valued the organic olive alternative very positively and much higher than the integrated and conventional options. The integrated group, on the other hand, ranked the integrated olive system highest, followed by the organic option and then the conventional system. The opinion expressed by the conventional experts was similar to that of the organic experts but more restrained. However, despite the differences in opinion, they all appear to consider conventional olive-growing techniques as the least appropriate option to achieve the environmental objectives set.

In the literature, much debate and contradictory empirical evidence exists when comparing some particular environmental consequences of organic and conventional farming[46,47]. However, a better overall environmental performance of the organic olive system over the conventional method is in keeping with the conclusions drawn by other studies, such as a Europe-wide study[48], a UK study[49] and research carried out on Tuscan farming systems[50]. Another study[42] also demonstrated the better overall environmental performance of organic farming as opposed to integrated systems in Tuscany (Italy).



	Conventional olive farming	Organic olive farming	Integrated olive farming
ConExp	0.290	0.367	0.342
OrgExp	0.241	0.463	0.295
IntExp	0.253	0.324	0.423
Mean	0.262	0.386	0.352

Figure 5. Overall environmental performances of the three farming systems according to the different groups of experts and the mean opinion of the three groups of experts. ConExp = Conventional experts; OrgExp = Organic experts; IntExp = Integrated experts; Mean = Mean of the three groups.

Table 2. Sensitivity analysis for the overall environmental performances.

Ranking frequency	1	2	3
ORG	782	218	0
INT	218	782	0
CON	0	0	1000
Pattern frequency			
ORG>INT>CON	782		
INT>ORG>CON	218		

ORG = Organic olive farming; INT = Integrated olive farming; CON = Conventional olive farming.
Ranking frequency: number of times an alternative is ranked in a specific position in the 1000 simulation process. Pattern frequency: frequencies of the obtained patterns of the prioritization of the alternatives.

Sensitivity analysis

An important subsequent step in the assessment of the alternatives is to determine the reliability of the obtained results based on a sensitivity analysis involving an ex-post examination of the performance of the proposed AHP model. The purpose of this analysis is to determine how the variation of the experts' judgments ($\omega_{L(i)}/\omega_{L(j)}$) in all nodes of the model at the same time would affect the overall environmental performances of the three farming systems. The value of the judgments will be randomly simulated within an interval around the mean judgment expressed by the experts [$(\omega_{L(i)}/\omega_{L(j)})_{\text{mean of the three types of experts}} \pm$ percentage]. The literature on this subject[22] recommends a percentage of variation between 5 and 15% depending on the level of the node in the hierarchy: 15% in the upper levels and 5% at the level of the alternatives, since uncertainty of the answers of experts should be theoretically greater in the upper levels. However, in our study we propose to relate this percentage of variation in each node to the local relative agreement degree in the node, because it refers precisely to the degree of dispersion of the answers given by the three types of experts in this node. The lower the relative agreement degree is, the greater the amplitude of the variation intervals. Furthermore, we use larger interval amplitudes with the aim of obtaining results that are even more reliable. Specifically, the equivalence between relative agreement degrees and amplitude of the intervals of variation was established as follows: Higher, 10%; Medium, 20%; Lower, 30%. For example, in a node with the lower relative agreement degree at local level, a judgment with a value of two according to the mean of the three types of experts, would be varied by 30%, that is, between $2*(1-0.3)$ and $2*(1+0.3)$, that is, between 1.4 and 2.6.

Once the judgment intervals were fixed, judgment values were simulated at random within these intervals for all the nodes in the model, according to a homogeneous distribution in our case, although other functions are also proposed in the literature. This process was repeated 1000 times, and different final priorities of the farming alternatives were obtained each time. In order to carry out this sensitivity analysis, 'Prior' and 'Estructura' software packages were used, which were developed in the Department of Statistical and Quantitative Methods of the University of Saragossa (Spain). Table 2 shows the results of this analysis at the goal level, although it has been carried out in all the nodes of the model. This table contains two sections: (1) the upper section is a set of cross cells which counts the number of times an alternative is ranked in a specific position in the 1000 simulation process. These numbers can be interpreted as the probability of an

Table 3. Direct and after sensitivity analysis prioritizations.

	Direct prioritization			After sensitivity analysis			Comparison		
	1°	2°	3°	1°	2°	3°	1°	2°	3°
Overall environmental performance	O	I	C	O	I	C	✓	✓	✓
1. Less soil erosion	I	O	C	I	O	C	✓	✓	✓
2. Soil fertility	O	I	C	I	O	C	✗	✗	✓
3. Rational use of irrig. water	O	I	C	I	O	C	✗	✗	✓
4. Less water contamination	O	I	C	O	I	C	✓	✓	✓
5. Less atmospheric pollution	O	I	C	O	I	C	✓	✓	✓
6. Biodiversity	O	I	C	O	I	C	✓	✓	✓

O = Organic olive farming; I = Integrated olive farming; C = Conventional olive farming.
✓/✗ = Coincidence/not coincidence of direct and after sensitivity analysis prioritizations.

alternative rank in a certain order; (2) the second section shows different patterns of the prioritization of the alternatives obtained in the simulation and their frequencies. These numbers can be interpreted as the probability that each pattern would actually occur. The sensitivity analysis confirms that the organic olive-growing system is perceived as environmentally more valuable than the integrated system, which is in turn better than the conventional method. This pattern ranking was the most probable, with a probability of 78.2%. However, this result can be qualified by saying that the integrated system has not got an inconsiderable probability of being considered the best from an overall environmental point of view. In fact, the integrated olive system could be the best option with a probability of 21.8%, according to our analysis.

We can say therefore that prioritization of the three growing methods at the overall level obtained directly via synthesis of priorities in a traditional way—direct prioritization—coincides with the prioritization obtained following the sensitivity analysis, considering the most likely pattern ranking. However, in other levels or criteria this might not occur. In this respect, both prioritizations have been compared in all nodes of the model. Table 3 shows a diagrammatic representation of this comparison, indicating whether the two arrangements do coincide or not. Prioritizations obtained were stable with the exception of the issues of *soil fertility* and the *rational use of irrigation water*, where it is unclear whether the organic olive-growing system or the integrated system achieves a better performance. This is in agreement with the literature on the subject which contains contradictory results regarding soil fertility in organic compared to conventional crops[42,51–53]. For the other issues, it seems clear that the best alternative is either (1) organic farming, at the *overall level*, for *less water contamination* and *less atmospheric pollution*, in accordance with previous studies[46,48,54], and *biodiversity*, in agreement with others[42,46,50,55,56], or (2) an integrated system, for *less soil erosion*, in agreement with other work[42].

Conclusions

A multi-criteria comparison of the environmental performances of conventional, organic and integrated olive farming systems in the south of Spain (Andalusia) has been carried out based on experts' knowledge. For this purpose the AHP has been implemented. It has shown itself to be a powerful and flexible tool for environmental assessment from a multi-criteria and holistic point of view. The utilization of experts' knowledge may help in decision-making processes where conventional information is not available, is partial or is demanding for time and resources. The multi-criteria analysis carried out based on experts' knowledge has enabled a wide range of information concerning diverse topics to be obtained. This generated multi-criteria information is useful in a context where the decision-making cannot be delayed or where a global perspective is required, such as in political decision-making, i.e., in situations where a holistic and multi-disciplinary perspective is preferred over a very detailed but narrow vision of reality. Implementation of AHP on the basis of experts' knowledge enables an easy, intuitive and sound comparative assessment of the multifunctional environmental performances of agricultural systems. This problem can be characterized by lack of information, complex nature of the criteria, and very high importance of the evaluated items on social welfare.

With regard to the obtained results, it must be pointed out that they are, in general, in agreement with previous partial studies, when available, which use different methodologies of analysis and are usually carried out in other regions and cultivations. In our case study, an important result is that, as a mean, organic and integrated farming systems are better valued than conventional farming by experts, from an overall environmental point of view and in the average conditions of Andalusia, thus confirming our initial hypothesis. That is, both farming systems have a greater environmental value in the medium to long-term, being more sustainable in the sense that they damage the

environment to a lesser degree compared to conventional agriculture. The better environmental performance of these alternative farming systems is probably related to the wider implementation, at least in the organic system, of more rational farming practices in the olive cultivation in Andalusia[41]. Quantification of the environmental performances of the three farming systems enables us to state that, in the average conditions of Andalusia, the environmental values of organic and integrated olive-growing systems are, respectively, 47 and 34% higher than that of the conventional system. These figures could approximate the fair levels of compensation that society owes to olive farmers who cultivate according to these two environmental friendly forms of agriculture. Probably, a cause of the low spread of these alternative practices could be that these levels of economic compensation are still not achieved and just the more 'idealistic', more environmentally concerned farmers are more inclined to adopt these methods[57].

Although prioritizations of the relative performances of the three farming systems are confirmed by the sensitivity analysis carried out, it is important to highlight that the environmental superiority of the two alternatives to conventional farming refers to the mean performances of these farming systems, whereas there could be a great variation in the environmental impact caused by individual farmers[47]. In any case, our results reflect the opinions of experts. Although experts were urged to express opinions in a way as objective as possible, an intrinsic subjective component may arise, the magnitude of which is difficult to quantify. In this sense, the proposed methodological extension of AHP along with the sensitivity analysis enabled us to detect effectively the more controversial items, and detect an 'ideological' subjective component in the opinions of experts. In effect, discrepancies among opinions and assessments of the three types of experts were detected in some topics, in agreement with our initial hypothesis: the organic and integrated interviewed experts showed a bias in their answers towards the alternative they are affiliated with. However, at the overall level, that is, with regard to the global environmental performances of the three farming systems, these discrepancies were not very high. Detection of the more controversial items in the model is of use to define new research areas where more in-depth knowledge is required, and subsequently to use this new knowledge to feed-back to the model with the new information and improve the decision process and the assessment of the three farming systems.

With respect to the analyzed sub-criteria the results are mixed. The organic olive farming system seems to be clearly superior over the integrated system, which is, in turn, better than the conventional method, with respect to biodiversity, less atmospheric pollution and less water contamination. The issues of erosion and soil fertility are more controversial, with the degree of relative agreement among experts being the lowest of all the topics. However, despite the polemic, integrated olive farming system seems to be a better alternative against erosion according to the sensitivity analysis. The rational use of irrigation water is also a controversial issue, being not possible to state a clear superiority of organic over integrated farming or vice versa. Finally, it is interesting to underline that for all the analyzed topics the conventional olive system received the lowest assessment from the experts.

References

1. European Commission. 1985. The Green Book: Perspectives for the Common Agricultural Policy. Communication of the European Communities to the Council, document com(85) 333 final, Brussels.
2. WCED—World Commission on Environment and Development. 1987. Our Common Future. Brundtland Report.
3. United Nations. 1992. Report on Environment and Development (Agenda 21). Annex II, UN Document A.Conf.151.26.
4. United Nations. 1992. Rio Declaration on Environment and Development. UN Document A/Conf.151/5/Rev.1.
5. European Commission. 1996. The Cork Declaration: A living countryside. European Conference on Rural Development: Rural Europe – Future Perspectives, Cork, Ireland, 7–9 November.
6. Directorate-General for Agriculture of the European Commission. 2003. Reform of the Common Agricultural Policy: Medium-term prospects for agricultural markets and income in the European Union 2003–2010. Available at Web site: http://europa.eu.int/comm/agriculture.
7. Asociación Española Laboreo de Conservación-Suelos Vivos. 1999. Cubiertas Vegetales en Arboricultura Frutal. Ficha Técnica n° 5. Available at Web site: http://www.aeac-sv.org/pdfs/ficha5.pdf.
8. Labrador Moreno, J. and Guiberteau Cabanillas, A. 1990. La Agricultura Ecológica. Hojas divulgadoras N°11/90HD. MAPA, Dirección General de Investigación y Capacitación Agrarias.
9. Parra-López, C. and Calatrava-Requena, J. 2005. Factors related to the adoption of organic farming in Spanish olive orchards. Spanish Journal of Agricultural Research 3(1):5–16.
10. Saaty, T.L. 1977. A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology 15:234–281.
11. Saaty, T.L. 1980. The Analytic Hierarchy Process. McGraw Hill, New York. Reprinted in 1996 by RWS Publications, Pittsburgh.
12. Saaty, T.L. 1994. The Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process, Vol. 6. AHP Series. RWS Publications, Pittsburgh.
13. Tiwari, D.N., Loof, R., and Paudyal, G.N. 1999. Environmental-economic decision-making in lowland irrigated agriculture using multi-criteria analysis techniques. Agricultural Systems 60(2):99–112.
14. Mendoza, G.A. and Prabhu, R. 2000. Multiple criteria decision making approaches to assessing forest sustainability using criteria and indicators: a case study. Forest Ecology and Management 131:107–126.
15. Bernetti, I., Casini, L., Romano, D., and Scotti, R. 1994. Environmental and land use issues in Multi-Purpose Forest Management: An application to the Vallombrosa National Forest (Tuscany). 34th EAAE Seminar. Available at Web

site: http://www.unifi.it/unifi/deeaf/bernettiWEB/download/pubblica/p31.pdf.
16. Peterson, D.L., Silsbee, D.G., and Schmoldt, D.L. 1995. A Planning Approach for Developing Inventory and Monitoring Programs In National Parks. Work document, U.S. Department of the Interior National Park Service. Available at Web site: http://www.nature.nps.gov/im/monitor/peterson.pdf.
17. Pirazzoli, C. and Castellini, A. 2000. Application of a model for evaluating the environmental sustainability of cultures in hill and mountain areas. Agricultural Economics Review 1:57–70.
18. Duke, J.M. and Aull-Hyde, R. 2002. Identifying public preferences for land preservation using the analytic hierarchy process. Ecological Economics 42:131–145.
19. Hernández, A. and Cardells, F. 1999. Aplicación del método de las jerarquías analíticas a la valoración del uso recreativo de los espacios naturales de Canarias. Working paper, Gobierno de Canarias. Available at Web site: http.//www.gobcan.es/medioambiente/revista/1999/13/61/index.html.
20. Reyna, D.S. and Cardells, R.F. 1999. Valoración AHP de los ecosistemas naturales de la Comunidad Valenciana. Revista Valenciana D'Estudis Autonomics 27:153–179.
21. Escobar, M.T. and Jiménez, J.M.M. 1994. Técnicas multicriterio discretas en la planificación de cuencas fluviales. Estudios de Economía Aplicada 1:7–29.
22. Moreno Jiménez, J.M. 1997. Priorización y toma de decisiones ambientales. Proceedings from I Encuentro Iberoamericano sobre Evaluación y Decisión Multicriterio. July, Santiago de Chile.
23. Moreno Jiménez, J.M., Aguarón, J., Escobar, M.T., and Turón, A. 1999. The Multicriteria Procedural Rationality on SISDEMA. European Journal of Operational Research 119(2):388–403.
24. Moreno Jiménez, J.M., Aguarón, J., and Escobar, M.T. 2001. Metodología científica en valoración y selección ambiental. Pesquisa Operacional 21:3–18.
25. Brunner, N. and Starkl, M. 2004. Decision aid systems for evaluating sustainability: a critical survey. Environmental Impact Assessment Review 24(4):441–469.
26. Forman, E. and Selly, M.A. 2001. Decisions by Objectives. Expert Choice Inc. Available at Web site: http://www.expertchoice.com.
27. Forman, E., Saaty, T.L., Selly, M.A., and Waldron, R. 1983. Expert Choice. Decision Support Software. McLean, VA.
28. Saaty, T.L. 1996. Decision Making with Dependence and Feedback: The Analytic Network Process. RSW Publications, Pittsburgh. Reprinted in 2001.
29. Ramanathan, R. and Ganesh, L.S. 1994. Group preference aggregation methods employed in AHP: an evaluation and an intrinsic process for deriving member's weightages. European Journal of Operational Research 79:249–265.
30. Forman, E. and Peniwati, K. 1998. Aggregating individual judgements and priorities with the Analytic Hierarchy Process. European Journal of Operational Research 108:165–169.
31. Aczél, J. and Saaty, T.L. 1983. Procedures for synthesizing ratio judgements. Journal of Mathematical Psychology 27(1):93–102.
32. Saaty, T.L. 1989. Group decision making and the AHP. In B.L. Golden, E.A. Wasil, and P.T. Harker (eds). The Analytic Hierarchy Process. Applications and Studies. Springer-Verlag, Berlin. p. 59–67.
33. Zahir, S. 1999. Clusters in a group: decision making in the vector space formulation of the analytic hierarchy process. European Journal of Operational Research 112:620–634.
34. Zahir, S. 1999. Geometry of decision making and the vector space formulation of the analytic hierarchy process. European Journal of Operational Research 112:373–396.
35. Shirani, A., Aikèn, M., and Paolillo, J.G.P. 1998. Group decision support systems and incentive structures. Information and Management 33(5):231–240.
36. Bryson, N. 1996. Group decision-making and the analytic hierarchy process: Exploring the consensus-relevant information content. Computers and Operations Research 23(1):27–35.
37. Bryson, N. 1997. Consensus formation in group support systems using the qualitative discriminant process. Annals of Operations Research 71:75–91.
38. Yeh, J.M., Kreng, B., and Lin, C. 2001. A consensus approach for synthesizing the elements of comparison matrix in the Analytic Hierarchy Process. International Journal of Systems Science 32(11):1353–1363.
39. Junta de Andalucía. 2004. Anuario de Estadísticas Agrarias y Pesqueras de Andalucía-2001. Consejería de Agricultura y Pesca, Servicio de Publicaciones y Divulgación.
40. Pastor, M., Caballero, J.I., Alvarado, M., and Civantos, M. 2000. La Producción Integrada en olivar en la Comunidad de Andalucía, Vida Rural 105. Available at Web site: http://www.eumedia.es/articulos/vr/Aceites/1abrolivar.htm.
41. Parra-López, C. and Calatrava-Requena, J. 2006. Comparison of farming techniques actually implemented and their rationality in organic and conventional olive groves in Andalusia, Spain. Biological Agriculture and Horticulture 24(1): 35–59.
42. Pacini, C., Wossink, A., Giesen, G., Vazzana, C., and Huirne, R. 2003. Evaluation of sustainability of organic, integrated and conventional farming systems: a farm and field-scale analysis. Agriculture, Ecosystems and Environment 95:273–288.
43. Conacher, J. and Conacher, A. 1998. Organic farming and the environment, with particular reference to Australia: a review. Biological Agriculture and Horticulture 16: 145–171.
44. Sánchez Sánchez, J.L. 2003. Evaluación de Sustentabilidad de Sistemas de Manejo de Olivares Ecológicos y Convencionales en Los Pedroches. 4th edition 'Andrés Núñez de Prado' award-winning work. Asociación Comité Andaluz de Agricultura Ecológica—CAAE, Sevilla, Spain.
45. Rigby, D., Young, T., and Burton, M. 2001. The development of and prospects for organic farming in the UK. Food Policy 26(6):599–613.
46. Hansen, B., Alrøe, H.F., and Kristensen, E.S. 2001. Approaches to assess the environmental impact of organic farming with particular regard to Denmark. Agriculture, Ecosystems and Environment 83:11–26.
47. Rigby, D., Woodhouse, P., Young, T., and Burton, M. 2001. Constructing a farm level indicator of sustainable agricultural practice. Ecological Economics 39:463–478.
48. Stolze, M., Piorr, A., Häring, A., and Dabbert, S. 2000. The environmental impact of organic farming in Europe. Organic Farming in Europe: Economics and Policy, Vol. 6. University of Hohenheim, Germany.
49. Cobb, D., Feber, R., Hopkins, A., Stockdale, L., O'Riordan, T., Clements, B., Firbank, L., Goulding, K., Jarvis, S., and

Macdonald, D. 1999. Integrating the environmental and economic consequences of converting to organic agriculture: evidence from a case study. Land Use Policy 16:207–221.
50. Pacini, C., Wossink, A., Giesen, G., and Huirne, R. 2004. Ecological-economic modelling to support multi-objective policy making: a farming systems approach implemented for Tuscany. Agriculture, Ecosystems and Environment 102:349–364.
51. Siegrist, S., Schaub, D., Pfiffner, L., and Mäder, P. 1998. Does organic agriculture reduce soil erodibility? The results of a long-term field study on loess in Switzerland. Agriculture, Ecosystems and Environment 69:253–264.
52. Gunapala, N., Venette, R.C., Ferris, H., and Scow, K.M. 1998. Effects of soil management history on the rate of organic matter decomposition. Soil Biology and Biochemistry 30(14):1917–1927.
53. Hummel, R.L., Walgenbach, J.F., Hoyt, G.D., and Kennedy, G.G. 2002. Effects of vegetable production system on epigeal arthropod populations. Agriculture, Ecosystems and Environment 93:177–188.
54. DEPA. 1999. Økologiske scenarier for Danmark. Danish Environmental Protection Agency. Available at Web site: http://www.mst.dk/199903publikat/87-7909-292-6/oekologi.pdf.
55. Stockdale, E.A., Lampkin, N.H., Hovi, M., Keatinge, R., Lennartsson, E.K.M., Macdonald, D.W., Padel, S., Tattersall, F.H., Wolfe, M.S., and Watson, C.A. 2001. Agronomic and environmental implications of organic farming systems. Advances in Agronomy 70:261–262.
56. Freemark, K.E. and Kirk, D.A. 2001. Birds on organic and conventional farms in Ontario: partitioning effects of habitat and practices on species composition and abundance. Biological Conservation 101:337–350.
57. Parra-López, C., De Haro Giménez, T., and Calatrava-Requena, J. Forthcoming. Diffusion and adoption of organic farming in the southern Spanish olive groves. Journal of Sustainable Agriculture.

Renewable Agriculture and Food Systems: 22(3); 204–212 doi:10.1017/S1742170507001743

Vegetable crop emergence and weed control following amendment with different *Brassicaceae* seed meals

A.R. Rice[1], J.L. Johnson-Maynard[1,*] , D.C. Thill[2], and M.J. Morra[1]

[1]Division of Soil and Land Resources, University of Idaho, Moscow, ID 83844-2339, USA.
[2]Plant Science Division, University of Idaho, Moscow, ID 83844-2339, USA.
*Corresponding author: jmaynard@uidaho.edu

Accepted 27 September 2006 **Research Paper**

Abstract

Brassicaceae seed meals produced through the oil extraction process release biologically active glucosinolate secondary products and may be useful as a part of biological weed control systems. Before meal can be used most efficiently, recommendations for suitable planting dates that maximize weed control but reduce crop injury must be determined. Our objectives were to determine the impact of 1 and 3% (w/w) meal applications of *Brassica napus* L. (canola), *Brassica juncea* L. (oriental mustard) and *Sinapis alba* L. (yellow mustard) on crop emergence and weed biomass in a growth chamber and field study. Results from the growth chamber experiment indicated that lettuce emergence was reduced by at least 75% when planted into 3% *S. alba*-amended soil earlier than 5 weeks after meal application. After 5 weeks, emergence was not different among treatments. Crop emergence was not reduced by any meal treatment as compared to the no-meal treatment in year 1 of the field study. In year 2, crop emergence in each 1.2-m row was inhibited by all meal treatments and ranged from 16 plants in the 3% *B. juncea* treatment to 81 plants in the no-meal treatment. The difference between emergence results in year 1 and year 2 is likely due to differing climatic conditions early in the season prior to irrigation, and the method of irrigation used. Redroot pigweed (*Amaranthus retroflexus* L.) biomass was 72–93% lower in 1% *B. juncea* and 3% treatments relative to the no-meal control in the first weed harvest of year 1. These same treatments had 87–99% less common lambsquarters (*Chenopodium album* L.) biomass. By the second weed harvest, redroot pigweed biomass in meal treatments (0.02–1.6 g m^{-2}) was not different from that in the no-meal treatment (0.97 g m^{-2}). Redroot pigweed biomass in 3% *B. juncea* plots was reduced by 74% relative to the no-meal treatment in the first harvest of year 2. This treatment also reduced common chickweed [*Stellaria media* (L.) Vill.] biomass by 99% relative to the 1% meal treatments. While pigweed biomass was reduced by 3% *B. juncea* in the early part of the season, by the second harvest this same treatment had the greatest pigweed biomass. Despite significant variability between years, 3% *B. juncea* did provide early season weed control in both years. Repeated meal applications, however, may be necessary to control late season weeds. Inhibition of crop emergence appears to be highly dependent on the amount and distribution of water and needs to be further studied in field settings.

Key words: mustard meal, canola, biological weed control, lettuce, beets, allelopathy

Introduction

Allelopathy is defined as 'any process that involves secondary metabolites produced by plants, algae, bacteria and fungi that influences the growth and development of biological systems'[1]. The ability of allelopathic plants to inhibit seed germination, emergence, and growth may be useful as part of biologically based weed control systems[2,3]. Certain plants in the *Brassicaceae* family are known to possess allelopathic properties, and their use as cover crops is currently being studied in many different cropping systems[4].

Biologically active secondary compounds such as isothiocyanates (ITCs), ionic thiocyanates (SCN^-), nitriles, and oxazolidinethiones (OZT) are produced through the degradation of chemicals called glucosinolates that are found within *Brassicaceae* plant tissues[2,5–7]. Myrosinase, the enzyme responsible for catalysis of glucosinolate degradation, is physically separated from glucosinolates, thus preventing secondary glucosinolate product formation

© 2007 Cambridge University Press

in living plants[7–9]. Physical disruption of plant tissue through insect feeding or grinding is necessary for further degradation of the glucosinolates into ITCs and other secondary products[8–10].

Suppression of plant emergence by glucosinolate-derived allelochemicals has been documented[3,11]. Reduced germination of wheat planted into pots amended with either chopped black mustard [*Brassica nigra* (L.) Koch] or garden cress (*Lepidium sativum* L.) tissues has been reported[5]. In the same study, highly volatile allyl-ITC released by *Brassica juncea* tissue was found to be as effective as the commercial soil fumigant methyl ITC at inhibiting germination of several crop species[5]. A greenhouse study by Ju et al.[3] showed that SCN^-, released by *Sinapis alba*[12], inhibited the growth of tobacco and bean. Spiny sowthistle [*Sonchus asper* (L.) Hill], scentless mayweed (*Matricaria inodora* L.), barnyardgrass [*Echinochloa crusgalli* (L.) Beauv.], and blackgrass (*Alopecurus myosuroides* Huds.) were susceptible to the allelochemicals produced by *B. juncea* and *Brassica napus* mulches in a greenhouse study[11]. ITCs appear to be capable of inhibiting germination while seeds are still in the dormant stage[13], suggesting that they not only inhibit growth, but also germination.

The studies discussed above have focused on the allelopathic properties of *Brassicaceae* tissues either in fields where *Brassicaceae* crops have been used as green manures or cover crops, or in greenhouse studies where chopped tissues have been added to soil. While results of these studies generally report a significant reduction in weed seed germination, cover cropping may not be applicable in northern latitudes where the growing season is limited. An alternative to the use of the *Brassicaceae* cover crops is the seed meal, a by-product of the commercial oil pressing process for food and industrial oil and biodiesel production. Glucosinolates are concentrated within the seed material and are retained in the cold-crushing procedure[12] used in this study. An advantage of use of the meal is that myrosinase is preserved during crushing[2], but the low moisture content of the meal allows glucosinolates to remain stable in storage for extended periods of time. Once in contact with moisture, glucosinolate degradation to secondary allelopathic compounds is initiated[14].

ITCs and other glucosinolate hydrolysis products released by *Brassicaceae* seed meal can inhibit crop seed germination, potentially limiting its use[2]. Published studies of suitable planting dates for vegetable crops known to be sensitive to ITCs, however, are not found in the current literature. In order for *Brassicaceae* meal to be a viable and feasible means of weed control in farming systems, planting dates that optimize weed control, but reduce the phytotoxic potential of the allelopathic compounds to the crop must be determined, especially when crops are seeded directly into meal-amended soils. The main objective of this work was to determine suitable planting dates for lettuce, a crop known to be highly sensitive to ITCs[2] in a growth chamber study. The potential of several *Brassicaceae* meals to inhibit weed and crop seed germination in the field was also investigated.

Materials and Methods

Seed meal characterization

Meal was defatted and the glucosinolate concentrations determined using methods similar to that of the International Organization of Standardization[15] as modified and reported by Borek and Morra[12]. The procedure includes glucosinolate extraction with a 70% methanol/water solution and addition of 4-methoxybenzyl glucosinolate as an internal standard. Glucosinolates were then isolated using a DEAE anion exchanger and desulfated with sulfatase (Sigma-Aldrich, St. Louis, MO), after which time the samples were analyzed on a Waters 2695 HPLC separation module coupled with a Waters 996 photodiode array detector (PDA) and Thermabeam Mass Detector (TMD). Glucosinolates were identified with a combination of expected retention behavior (time, sequence) and their mass spectra, and quantified using response factors[16]. Total C and N contents of the meals were determined by dry combustion[17] using a C/N/S analyzer (Elementar, Hanau, Germany).

Growth chamber study

A high-glucosinolate meal (*S. alba*), low-glucosinolate meal (*B. napus*), and no-meal treatment were used to determine the impact of active secondary products on lettuce germination over time. Pots (10.2 cm × 10.2 cm) were filled with soil collected from a local organic-certified farm and amended with either 3% *B. napus*, 3% *S. alba*, or no seed meal. The soil was gently ground, passed through a 2-mm sieve and completely mixed prior to being placed in pots. The experiment was designed as a complete randomized block with ten replicates and was repeated twice. Growth chambers were maintained at 60% relative humidity, 24/21°C day/night temperature, and a 14-h photoperiod. Pots were surface-amended with meal every week for 6 weeks so a staggered succession of meal application dates occurred. Soil in pots was uniformly watered once a day and was not disturbed except at planting. Sixteen lettuce seeds were planted 1 week after the last meal application. All seeds were from the same seed lot and source. Emergence was determined by counting plants 3, 7, 10 and 14 days after planting.

Field methods

A field study was conducted on a certified organic farm in the Palouse region of northern Idaho. The soil was classified as Driscoll–Larkin silt loam, a Mollisol association[18]. For 3 years previous to the study, the field was fallowed and weeds were controlled using mechanical methods. The experimental design was a randomized

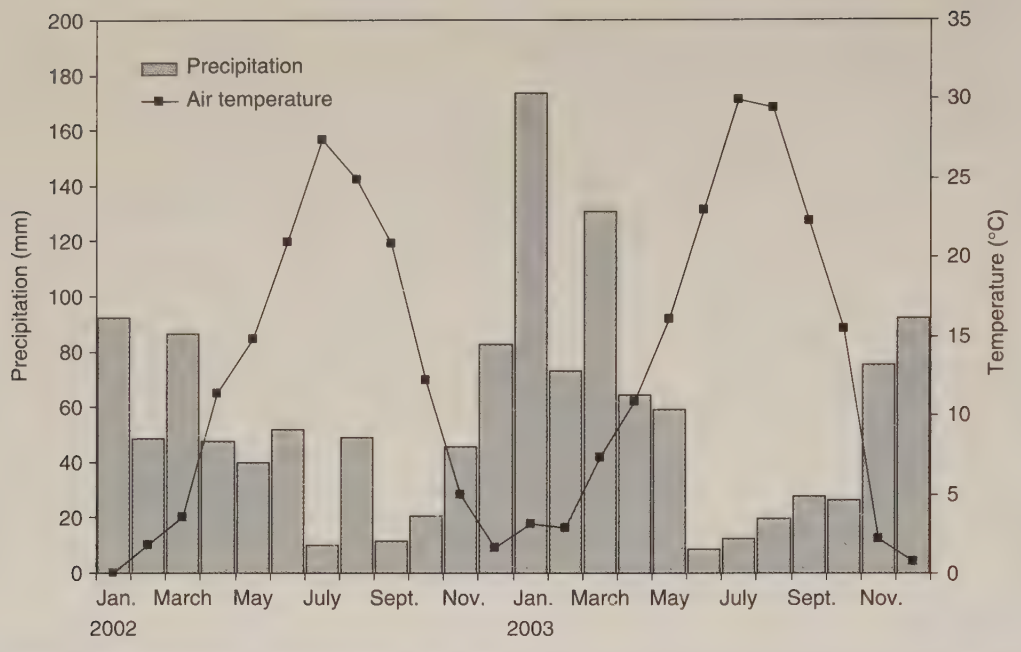


Figure 1. Total monthly precipitation and average monthly air temperature recorded for both years of the study. Data were recorded at a weather station located in Moscow, Idaho, approximately 8 km from the study site.

complete block split plot with six blocks as replicates and two crops as the split plot. Individual plots were 1.2 m^2 with 0.3-m borders between plots and a 1.5-m border around the entire site. Plots were re-located to a new area (approximately 20 m from the first plots) within the same field in the second year to eliminate any residual effects of the meal. Meal was obtained from the varieties Ida Gold (*S. alba*), Pacific Gold (*B. juncea*), and Athena and Sunrise (*B. napus*). Sunrise was used during the second year because Athena seed was not available. Treatments in year 1 included 1% *B. napus*, 3% *B. napus*, 1% *B. juncea*, 3% *B. juncea*, and no seed meal. Based on results from year 1, a second high-glucosinolate meal (*S. alba*) was added to the experimental design and treatments included 1% *B. napus*, 3% *B. napus*, 1% *B. juncea*, 3% *B. juncea*, 1% *S. alba*, 3% *S. alba*, and no seed meal in year 2. The seed meal rates of 1% (503 g meal $plot^{-1}$) and 3% (1509 g meal $plot^{-1}$) were chosen based on unpublished laboratory data that showed that these were the minimum rates necessary to control weeds, while minimizing phytotoxicity to the seeded crops. The weight of meal added to each plot was calculated on a meal : air-dry soil weight basis and a 3-cm depth of incorporation. The weight of soil in each plot was calculated using bulk density (mean value of 1.13 g cm^{-3}) measured by the core method[19]. A single application of meal was incorporated into all treatment plots with a rototiller on the same day. Lettuce and beets were chosen as crops for this study based on differences in seed size. Research has indicated that allelopathic sensitivity is possibly dependent on the size of the seed[11].

In the first year, plots were seeded on May 20, 14 days after meal application. Germination was extremely poor and the plots were re-planted 14 days later on June 3. Plots were planted 28 days after meal application during the second year (June 22). The seeding rates were determined based on the supplier's suggested rate that resulted in a 0.64-cm seed spacing for both beets and lettuce. Neither beet nor lettuce stands were thinned. Seeds were all obtained from the same source although lots varied between years. All plots were cleared of weeds at the time of seeding.

Since moisture is required for the production of secondary glucosinolate products, meal-amended plots were irrigated prior to planting in year 1, using a drip system. In year 2, precipitation from March to May equaled 255 mm, 80 mm greater than the amount received during this same time period in year 1 and 60 mm greater than the 30-year average value (Fig. 1). Due to wet field conditions, meal application, seeding, and weed and crop harvests in year 2 were carried out approximately 3 weeks later than in year 1. Irrigation in year 2 was not initiated until a week prior to planting and an overhead sprinkler was used. Although sprinkler and drip irrigations have been shown to produce similar lettuce yields[20], the use of two different irrigation systems in this study may complicate comparisons of seedling emergence between years. However, any impact of irrigation type on germination within a year should have been equal across all treatments.

Stands were assessed once each year by counting the number of crop plants that emerged in the entire middle row (1.2 m) within each plot. Weed biomass was determined two times during the growing season, on 25 June and 15 July for year 1 and 14 July and 11 August for year 2. Biomass of each weed species present in each 1.2-m^2 plot was collected by clipping at the soil surface. The biomass was dried in an oven at 60°C for 48 h and weighed.

Table 1. Glucosinolate concentrations in *Brassicaceae* seed meals.

Glucosinolate R-group (response factor)	*Brassica napus* 'Athena'	*B. napus* 'Sunrise'	*Sinapis alba* 'Ida Gold'	*Brassica juncea* 'Pacific Gold'
	----------μmol g^{-1} of sample----------			
(2*R*)-2-hydroxy-3-butenyl (1.09)	1.5 (0.30)	1.3 (0.09)	3.4 (0.25)	0.5 (0.18)
2-propenyl (1.00)				123.8 (15.31)
(2*S*)-2-hydroxy-3-butenyl (1.09)	0.4 (0.05)			
2-hydroxy-4-butenyl (1.09)	0.2 (0.09)		1.8 (0.66)	
(2*R*)-2-hydroxy-4-pentenyl (1.09)				0.5 (0.12)
4-hydroxy-benzyl (0.28)			148.1(26.75)	
Unknown (1.00)			9.1 (1.71)	
3-butenyl (1.11)	2.8 (0.60)	2.7 (0.31)		
4-hydroxy-3-indolylmethyl (0.28)	11.3 (3.52)	10.9 (3.25)		0.7 (0.26)
Unknown (1.00)			2.6 (0.75)	
Unknown (1.00)			0.74 (0.15)	
4-pentenyl (1.11)	1.3 (0.29)	1.4 (0.30)		
3-indolylmethyl (0.29)	0.9 (0.19)	0.8 (0.21)		
4-methylthiobutyl (1.00)	1.7 (0.48)			
N-methoxy-3-indolylmethyl (0.29)		0.1 (0.02)	0.01 (0.04)	0.6 (0.08)
Unknown (1.00)				1.3 (0.17)
Total	20.1 (2.71)	17.2 (2.16)	165.8 (20.32)	126.1 (14.38)

Blanks indicate the absence of a particular glucosinolate within a meal type. Standard deviations (based on five subsamples taken from the same lot of bulked meal) are shown in parentheses following means.

Data were statistically analyzed using the general linear model within SAS (Release 8.02) software (SAS Institute Inc., Cary, North Carolina). Emergence data from the growth chamber study were transformed by using an arcsine square root transformation. Due to the uneven distribution of weed species across the plots (certain species were only found in one or two plots) weed biomass data were separated by weed species and only the most common species were evaluated statistically. Means were separated with a pairwise *t*-test based on $P < 0.05$.

Results and Discussion

Meal characterization

The meals selected for this study provided a range from high (*B. juncea* and *S. alba*) to low (*B. napus*) glucosinolate content. The two *B. napus* meals contained the lowest total glucosinolate concentrations, ranging from 17 μmol g^{-1} in Sunrise to 20 μmol g^{-1} in Athena (Table 1). Total glucosinolate concentrations in the mustard meals substantially exceeded those in the *B. napus* control meals with *S. alba* meal containing 166 μmol g^{-1} and *B. juncea* meal 126 μmol g^{-1} (Table 1). The inclusion of different meals allowed us to not only compare glucosinolate type but also concentration. The experimental design did not allow us to specifically identify possible impacts of the meal on soil physical properties; however, any such effects should have been consistent among meal treatments.

ITCs produced by the specific glucosinolates contained in each seed meal have unique allelopathic properties. Similar to the findings of Minchinton et al.[21], *S. alba* (variety Ida Gold) contained 4-OH-benzyl (Table 1), a glucosinolate that can form SCN^- [22] at pH values expected in soil[12]. SCN^- is known to inhibit seed germination and seedling emergence[3,22]. Mechanisms behind the toxicity of SCN^- are unclear, but a positive relationship between SCN^- tissue concentration and chlorosis has been demonstrated, suggesting that the physiological effect of SCN^- is related to its ability to chelate iron, thereby reducing iron availability for chlorophyll synthesis[3]. Similar to results reported by Quinsac et al.[23], the dominant glucosinolate in both *B. napus* varieties was 4-OH-indolyl-3-methyl (10.9–11.3 μmol g^{-1}). Although 4-OH-indolyl-3-methyl is a non-ITC-producing glucosinolate[2] it can potentially degrade to SCN^- in soil[24].

B. juncea (variety Pacific Gold) contained 2-propenyl glucosinolate (Table 1), consistent with the findings of Hanley et al.[25]. 2-Propenyl ITC has been shown to be inhibitory to a number of organisms[26]. Mechanisms for toxicity of 2-propenyl ITC are unclear, although it has been proposed that seed germination inhibition is a result of the ability of ITCs to bind to proteins, resulting in inhibition of metabolic processes[24].

The N contents of the low glucosinolate meals (5.2% for Athena and 5.3% for Sunrise) were similar, to those found in *S. alba* (5.8%) and *B. juncea* (5.6%) meals. The C : N ratios (8.5 : 1 for *B. juncea*, 8.1 : 1 for *S. alba*, and 9.1 : 1 for *B. napus*) were also similar, suggesting that

differences in C:N ratios among meals should not confound the allelopathic effect on germination or weed growth.

Growth chamber

Analysis of data from the first and second growth chamber experiments showed that the treatment means had the same rank order and thus data were combined over experiments and analyzed using a pooled analysis. Lettuce plant emergence was the same for 7- and 14-day counts, thus only the 14-day count is presented. Seedling emergence in the *B. napus* treatment was lower than emergence in the no-meal treatment when lettuce was planted 1 or 2 weeks after meal amendment, indicating that this treatment had a short-term effect on lettuce germination (Fig. 2). This may be due to the ability of 4-OH-indolyl-3-methyl found in *B. napus* meal to produce SCN^{-}[24] or the formation of non-glucosinolate-derived allelopathic products. Inhibition of lettuce seed germination by non-glucosinolate degradation products from *B. napus* seed meal has been suggested[2]. The authors of this previous study concluded that non-glucosinolate-derived compounds were probably responsible for inhibition of seed germination although such compounds were not identified[2]. In a two-year cover crop study, researchers found the high-glucosinolate mustard (var. Ida Gold) crops reduced weed biomass to the same degree as rapeseed (var. Dwarf Essex) and a low-glucosinolate canola (var. Hyola)[4]. Low-glucosinolate *B. napus* meal was also shown to suppress apple root infection by *Rhizoctonia* spp. and *Pratylenchus penetrans*[27]. Together, results of past research suggest that *B. napus* tissues do produce biologically active compounds that are not derived from glucosinolates. Our data, however, suggest that these compounds are active over a relatively short period of time under optimal environmental conditions and that lettuce emergence was no longer delayed when planted 2 weeks after meal amendment.

Emergence was 3–17% of planted seeds in *S. alba*-amended soil from week 1 to week 4 after meal application (Fig. 2), indicating that *S. alba* meal can suppress lettuce emergence if it is planted less than 5 weeks after meal application under these conditions. This corresponds to other literature suggesting that *S. alba* can inhibit plant emergence[13]. Although the influence of varying environmental conditions experienced in field situations on seedling emergence was not tested, the data suggest that it may be necessary to wait approximately 5 weeks before planting lettuce into meal-amended soil. Since lettuce grows best under cooler temperatures, meal must be applied early enough in the season to avoid temperatures above the optimum range for lettuce seed germination. Early season application dates may pose a problem in areas where the soil is too wet to work in early spring. Although it was not evaluated as part of this study, transplanting established plants may help reduce toxicity, allowing for earlier planting.

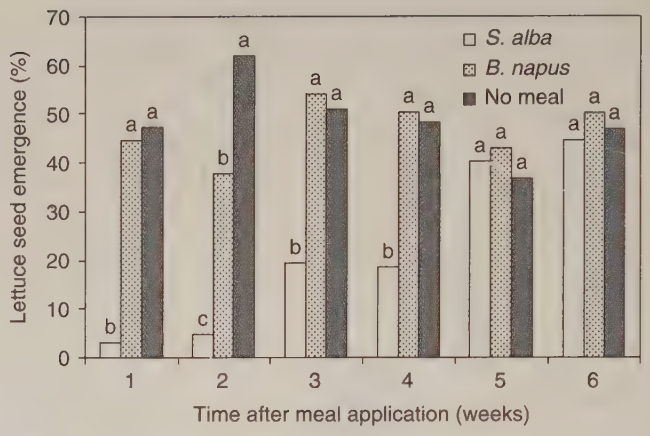


Figure 2. Emergence of lettuce seeds in 3% *B. napus*-, *S. alba*-, and no-meal-amended soils 2 weeks after planting in a growth chamber. Within a week, different letters indicate statistical difference among treatments.

It is important to note that the soils were kept moist throughout the growth chamber study. Pronounced wet and dry periods experienced in the field may alter the planting date to some extent, due to the requirement of moisture for the production of biologically active secondary compounds and its impact on volatilization, degradation reactions and leaching of these same compounds.

Field study

Lettuce and beet emergence. No significant interactions between crop and seed meal treatments for crop stand counts occurred in the field study for either year when crops were planted 28 days after meal amendment, thus the data are presented as averages for the two crops. For the first year, average stand counts, taken 22 days after planting, ranged from 39 plants per 1.2-m row in 1% *B. juncea* and 3% *B. napus* treatments to 23.5 plants per 1.2-m row in the no-meal treatment (Fig. 3A). Three percent *B. napus* and 1% *B. juncea* (both 39 plants per 1.2-m row) had significantly higher stand counts compared to the no-meal treatment (23.5 plants per 1.2-m row). Unlike data from year 1, emergence in the no-meal treatment was significantly higher (80.5 plants per 1.2-m row) than in all other treatments for the second year stand count (Fig. 3B). Crop emergence in the 3% *B. juncea* treatment (16.3 plants per 1.2-m row) was lower than in all other meal treatments.

Amendment with *B. napus* and *B. juncea* meals did not inhibit seedling emergence in year 1 compared to that measured in the no-meal plots when plots were seeded 28 days following meal application. This is consistent with results of the growth chamber study for *B. napus* that indicated no significant inhibition of germination after 2 weeks. In year 2, all meals reduced emergence relative to the no-meal treatment and 3% *B. juncea* inhibited crop emergence by at least 58% relative to the other meals when plots were seeded 28 days following meal application. The

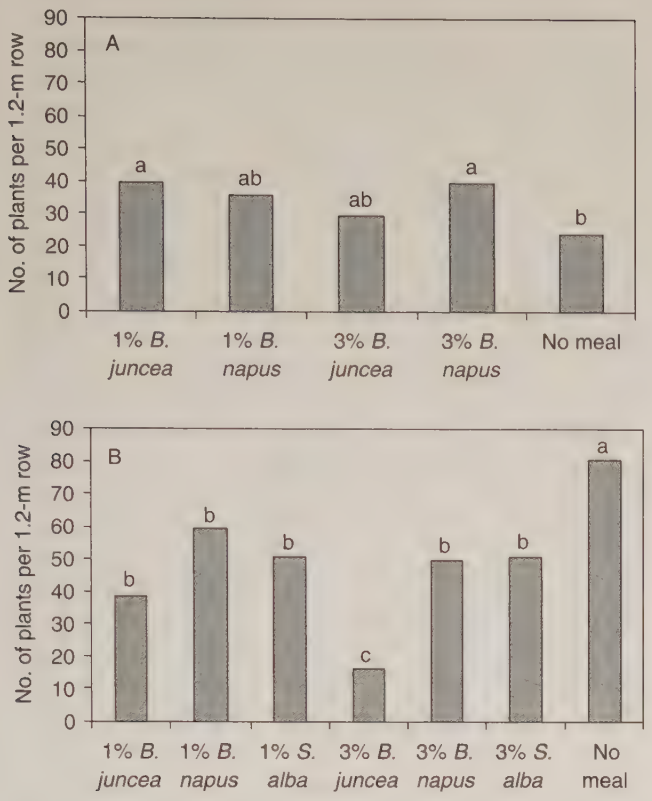


Figure 3. Crop stand counts for (A) year 1 and (B) year 2 of the field study. Data are pooled over beets and lettuce because there was no crop by seed meal interaction for either year. Different letters indicate statistical differences among treatments ($P < 0.05$).

only major differences between years 1 and 2 were in early season climatic conditions (80 mm more precipitation from March to May in year 2) (Fig. 1), type of irrigation system and the physical location of plots in the same field. Any impact of the change in plot location between years should have been apparent across all treatments and cannot explain inhibition in one year and not in the other, especially considering that the plots in both years were established in the same field. In year 1, irrigation water was added to the meal-amended plots using a drip system, while sprinklers were used in year 2. The lack of crop and weed emergence in the first planting in year 1 (14 days following meal application) indicated that sufficient water was present to initiate the formation of secondary glucosinolate products. Irrigation was continued during the 2-week period between the first and second seedings of year 1 ensuring that glucosinolate products were no longer being produced. Drip irrigation results in wetting of a relatively small area of soil[28], while the overhead sprinklers used in year 2 resulted in the wetting of the entire soil surface across each plot. Differences in wetting fronts could have altered the release and distribution of secondary products within the rooting zone between years, with the drip system favoring more rapid formation and disappearance (through volatilization or microbial decomposition) of secondary compounds.

Although we cannot entirely explain the variation between years, our field study results indicate that crop emergence can be reduced by high-glucosinolate seed meals. The data also highlight the importance of understanding the influence of environmental conditions and irrigation on the formation and retention of biologically active secondary compounds in field soils. The type and concentration of glucosinolates present in *S. alba* and *B. napus* meals are different (Table 1) yet these treatments inhibited emergence to the same degree in year 2 of the field study. This was not consistent with results of the growth chamber study. The lack of differences between these two treatments in the field after 28 days suggests that environmental conditions in the field allowed secondary compounds produced by *B. napus* to persist longer than was found in the growth chamber study (2 weeks). Distribution and losses of soluble SCN^- within the root zone in the field may have also been different than within the pots used in the growth chamber study.

Weed biomass

Due to the rarity of species in replicates (several species only occurred in one plot within a treatment) and the overall low weed biomass present, weed biomass from only the most predominant species present in each collection will be discussed. For the first weed biomass harvest during year 1, redroot pigweed and common lambsquarters were the dominant species present. Redroot pigweed biomass ranged from a mean of $3.5\,g\,m^{-2}$ in the no meal treatment to $0.26\,g\,m^{-2}$ in the 3% *B. napus* treatment. All meal treatments significantly reduced ($P = 0.027$–0.001) redroot pigweed biomass (59–93%) relative to the no-meal treatment (Fig. 4A). Biomass of common lambsquarters ranged from $0.01\,g\,m^{-2}$ in the 3% *B. napus* treatment to $1.18\,g\,m^{-2}$ in the no-meal treatment. All meals except 1% *B. napus* ($P = 0.109$), the lowest glucosinolate-containing meal, suppressed lambsquarters biomass relative to the no-meal treatment ($P = 0.0048$–0.0018). In the second weed harvest of year 1, redroot pigweed was the dominant species present and the only weed occurring in all treatments. Average redroot pigweed biomass ranged from $0.02\,g\,m^{-2}$ in the 1% *B. napus* meal treatment to $1.6\,g\,m^{-2}$ in the 1% *B. juncea* treatment (Fig. 4B). There was a marginally significant ($P = 0.056$) increase of redroot pigweed biomass in the 1% *B. juncea* treatment relative to that in plots treated with 1% *B. napus*.

Weed biomass in year 1 was low across all treatments. This is likely a reflection of the aggressive use of physical weed control methods such as tillage in the three-year fallow period previous to this study and the use of an efficient drip system that limits soil moisture outside of the crop rooting zone. Although the low weed biomass during year 1 makes interpretation of results somewhat difficult, both rates of *B. juncea* and the 3% *B. napus* treatment had significantly lower levels of redroot pigweed and common lambsquarters biomass in the first sampling. The lack of

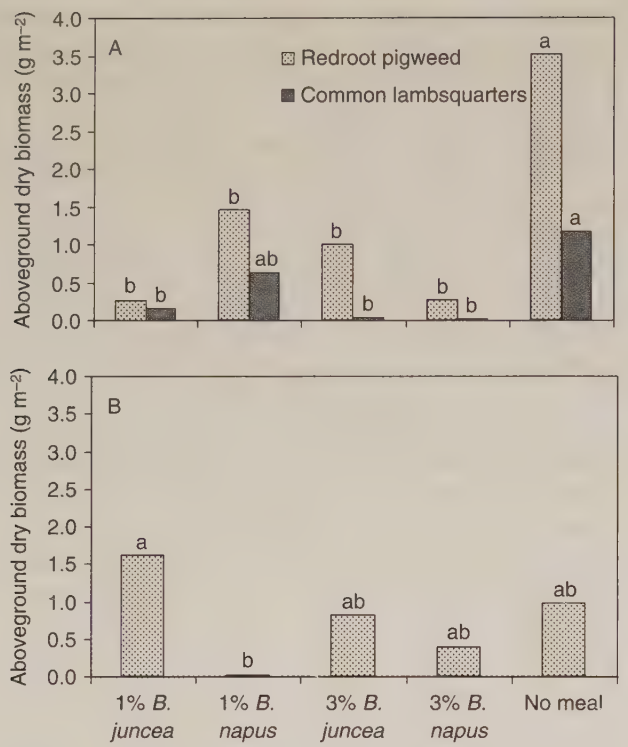


Figure 4. Biomass of the dominant weed species present during the (A) first and (B) second weed harvests of year 1. Differing letters indicate statistical differences among treatments ($P < 0.05$) within a weed species.

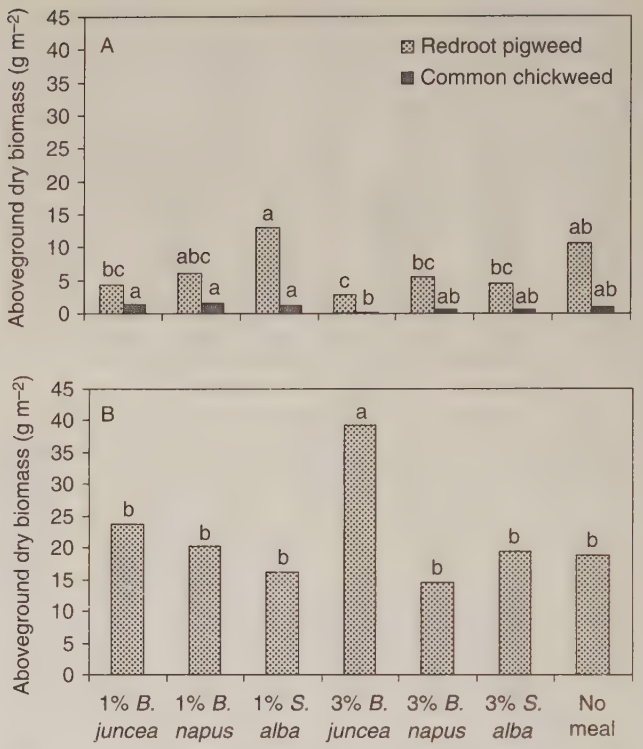


Figure 5. Biomass of the dominant weed species present during the (A) first and (B) second weed harvests of year 2. Differing letters indicate statistical differences among treatments ($P < 0.05$) within a weed species.

differences in weed biomass between meal treatments and the no-meal control during the second harvest indicates that weed control following meal application is short-term. This is consistent with laboratory results demonstrating the short half-lives (20–60 h depending on soil type) of ITCs in soil[14]. Concentrations of SCN^- are also expected to decrease relatively rapidly in soils (half-life of 60–120 h), as a result of microbial degradation[29].

The only weed species present in the first harvest of year 2 were redroot pigweed and common chickweed (Fig. 5A). Redroot pigweed was the dominant weed, with common chickweed making up only 4–23% of the total weed biomass within plots. Although it is difficult to clearly infer treatment effects, due to the low biomass of common chickweed present, biomass did tend to be higher in the 1% meal treatments (Fig. 5A) relative to the 3% treatments. Biomass of redroot pigweed was suppressed 74% by 3% *B. juncea* relative to the no-meal treatment and 3% *B. juncea* was the only treatment that inhibited redroot pigweed biomass compared to the no-meal treatment (Fig. 5A).

By the second harvest, redroot pigweed biomass within the 3% *B. juncea* treatment was 52% higher than it was in the no-meal treatment and was significantly higher than in all the other treatments (Fig. 5B). This is similar to the increase in redroot pigweed biomass in the 1% *B. juncea* treatment during the second harvest of year 1. Increased redroot pigweed biomass within *B. juncea* plots at the second harvest may be explained by direct and indirect impacts of this meal and the specific growth characteristics and requirements of this weed species. Redroot pigweed is considered a nitrophile[30] and therefore its growth may be favored by mineralized N in meal-amended plots following the dissipation of allelochemicals. Although the C : N ratio and total N content of each meal were similar, ITCs produced by *B. juncea* meal are known to directly impact micro-organisms[24], the group of soil organisms that are responsible for N mineralization. Application of *B. juncea* meal may, therefore, result in patterns of N mineralization different from those expected from non-biologically active materials with similar C : N ratios. The impact of specific glucosinolates on mineralization in meal-amended soils should be further researched. Redroot pigweed is also able to germinate at any time during the season if soil moisture is adequate[31]. The ability to germinate throughout the season combined with reduced competition due to the impact of 2-propenyl ITC produced by *B. juncea* meal on earlier weeds would give redroot pigweed a competitive advantage. The redroot pigweed data indicate that meal application may result in higher weed biomass later in the season after the allelopathic effect has dissipated. The ability to promote late season weeds may limit the use of meal or require repeated applications during the growing season.

Contrary to results in the growth chamber study, significant weed suppression was not apparent in the *S. alba* treatment, the seed meal expected to produce the

most pronounced herbicidal effects due to the formation of SCN^-[22]. The lack of statistical differences in weed biomass between *S. alba* and the no-meal treatment is likely due to a combination of the relatively high degree of variability in weed biomass and the expected behavior of SCN^- in soils. SCN^- has a relatively short soil residence time, with 40–95% being lost within a 6-day period in one study[29]. Although 2-propenyl ITC released by *B. juncea* meal also has a short half-life of 20–60 h[14], it is likely that the high precipitation plus irrigation water added during the second year resulted in retention of 2-propenyl ITC while the SCN^-, being more water soluble and less volatile than 2-propenyl, was leached through the soil profile. Thus, it is likely that SCN^- concentrations in the soil were low enough at the end of the 28-day-period before planting that it had no detectable influence on weed emergence. Because weeds were removed at the time of planting, any impacts of meal application on weed biomass prior to planting were not quantified.

Despite the difference in environmental conditions, irrigation, and planting and harvesting dates between years, 3% *B. juncea* inhibited early season (first harvest) weed biomass relative to the no-meal treatment in both years. The lack of significant differences between weed biomass in 3% *B. juncea* (high glucosinolate) and 3% *B. napus* (low glucosinolate) treatments during the first harvests indicates that glucosinolates may not be the only allelochemicals causing the reduction of weed biomass. The lack of weed control in the second harvests of both years indicates that meal application provides short-term weed control. An additional concern is an increase of redroot pigweed biomass in the second collections. The data suggest that weeds that are able to germinate throughout the year, or later in the growing season when temperatures are high, may benefit from mineralized N and/or lower competition once secondary agents that have relatively short half-lives in soil are no longer present.

Conclusion

Data from the growth chamber study suggest that sensitive crops such as lettuce should not be seeded directly into fields amended with high glucosinolate meals until 5 weeks after application. Meal, therefore, may need to be applied when relatively wet conditions are present in the field. For crops sensitive to ITCs, transplanting established seedlings or increasing the seeding density may help increase plant survival and yields in meal-amended soils. The influence of glucosinolate-derived secondary products on crop emergence appears to be highly dependent on soil moisture conditions. The negative impacts of relatively soluble SCN^- produced from *S. alba* meal may not be as drastic as expected from the growth chamber study, due to leaching of this soluble compound in irrigated field soils.

The field study results suggest that *Brassicaceae* meal can be used to control early season weeds. These results were most consistently seen with the 3% *B. juncea* amendment. Single applications of meal, however, will likely not be adequate to control weeds throughout the growing season and may result in higher late-season weed biomass due to possible increases in plant-available nitrogen and reduced intraspecific competition. For these reasons, meal may not be a suitable method of weed control in all systems. Meal amendments, however, may still be beneficial in organic-certified fields. Without the use of synthetic pesticides organic growers face significant challenges relating to weed control[32,33] and therefore may especially benefit from any ability to control early season weeds if conditions allow early application of meal.

Due to the dependence of ITC formation and degradation on soil moisture conditions, climatic conditions and irrigation practices must also be accounted for when determining planting dates. Further understanding of the mode of action and persistence of glucosinolate secondary products under field conditions needs to be gained to better predict planting dates that avoid crop inhibition.

Acknowledgements. This work was made possible through a grant from the Organic Farming Research Foundation (http://www.ofrf.org/). We also thank the owner and operator, Mary Jane Butters, and staff of Paradise Farm Organics for providing space and support for the field experiment. We also acknowledge Karl Umiker, Heidi Heffernan, Vladimir Borek, and Pauline Wanjugi for their assistance with field and laboratory work.

References

1. Mallik, A. 2005. Allelopathy: advances, challenges and opportunities. In J.D.I. Harper, M. An, H. Wu, and J.H. Kent (eds). Proceedings of the 4th World Congress on allelopathy, Charles Sturt University, Wagga Wagga, NSW, Australia. International Allelopathy Society. Available at Web site http://www.regional.org.au/au/allelopathy/2005 (verified 4 November 2006).
2. Brown, P.D. and Morra, M.J. 1996. Hydrolysis products of glucosinolates in *Brassica napus* tissues as inhibitors of seed germination. Plant and Soil 181:307–316.
3. Ju, H.Y., Bible, B.B., and Chong, C. 1983. Influence of ionic thiocyanate on growth of cabbage, bean, and tobacco. Journal of Chemical Ecology 8:1255–1262.
4. Haramoto, E.R. and Gallandt, E.R. 2005. *Brassica* cover cropping: I. Effects on weed and crop establishment. Weed Science 53:695–701.
5. Vaughan, S.F. and Boydston, R.A. 1997. Volatile allelochemicals released by crucifer green manures. Journal of Chemical Ecology 23:2107–2116.
6. Vaughn, S. 1999. Glucosinolates as Natural Pesticides: Agrochemicals. CRC Press, Boca Raton, FL.
7. Petersen, J., Belz, R., and Walker, F. 2001. Weed suppression by release of isothiocyanates from turnip–rape mulch. Agronomy Journal 93:37–43.
8. Bagger, C., Buskov, J.B., Hasselstrom, J.B., Jorgen, B., Rosa, E.A.S., Sorensen, H., and Sorenson, J.C. 1999. Bioactives from Cruciferous crops especially glucosinolate derived products produced in pilot plant scale and used as biocides supplementary to synthetic pesticides. In Proceedings of the

10th International Rapeseed Congress, Canberra, Australia, 26–29 September [CD Rom].
9. Bending, G.D. and Lincoln, S.D. 1999. Characterisation of volatile sulphur-containing compounds produced during decomposition of *Brassica juncea* tissues in soil. Soil Biology and Biochemistry 31:695–703.
10. Warton, B., Matthiessen, J.N., and Shackleton, M.A. 2001. Glucosinolate content and isothiocyanate evolution—two measures of the biofumigation potential of plants. Journal of Agriculture and Food Chemistry 49:5244–5250.
11. Petersen, J., Belz, R., Walker, F., and Hurle, K. 2001. Weed suppression by release of isothiocyanates from turnip–rape mulch. Agronomy Journal 93:37–43.
12. Borek, V. and Morra, M.J. 2005. Ionic thiocyanate (SCN^-) production from 4-hydroxybenzyl glucosinolate contained in *Sinapis alba* seed meal. Journal of Agriculture and Food Chemistry 53:8650–8654.
13. Vaughan, S.F. and Boydston, R.A. 1995. Phytotoxicity of *Brassica* spp. volatiles to weed and crop seed germination and growth. In C.C. Kupatt (ed.). Weed Science Society of America Abstracts, p. 55.
14. Borek, V., Morra, M.J., Brown, P.D., and McCaffrey, J.P. 1995. Transformation of the glucosinolate-derived allelochemicals allyl isothiocyanate and allyl nitrile in soil. Journal of Agriculture and Food Chemistry 43:1935–1940.
15. International Organization of Standardization. 1992. Rapeseed-determination of Glucosinolate Content. Part 1: Method using High-performance Liquid Chromatography, ISO 9167–1:1992(E). International Organization of Standardization, Geneva, Switzerland.
16. Wathelet, J., Lori, R., Leoni, O., Rollin, P., Quinsac, A., and Palmieri, S. 2004. Guidelines for glucosinolate analysis in green tissues used for biofumigation. Agroindustria 3:257–266.
17. Nelson, D.W. and Sommers, L.E. 1996. Total carbon, organic carbon, and organic matter. In D.L. Sparks (ed.). Methods of Soil Analysis. Part 3: Chemical Methods. American Society of Agronomy–Crop Science Society of America–Soil Science Society of America, Madison, WI. p. 961–1010.
18. Soil Survey Staff. 1981. Soil Survey of Latah County Idaho. USDA-Natural Resource Conservation Service US Govt, Print Off., Washington, DC.
19. Grossman, R.B. and Reinsch, T.G. 2002. Bulk density and linear extensibility. In J.H. Dane and G.C. Topp (eds). Methods of Soil Analysis. Part 4. American Society of Agronomy–Crop Science Society of America–Soil Science Society of America, Madison, WI. p. 201–225.
20. Sammis, T.W. 1980. Comparison of sprinkler, trickle, subsurface, and furrow irrigation methods for row crops. Agronomy Journal 72:701–704.
21. Minchinton, I., Sang, J., Burke, D., and Truscott, R.J.W. 1982. Separation of desulphoglucosinolates by reversed-phase high-performance liquid chromatography. Journal of Chromatography 247:141–148.
22. Beekhuis, H.A. 1975. Technology and industrial applications. In A.A. Newman (ed.). Chemistry and Biochemistry of Thiocyanic Acid and its Derivatives. Academic Press, London. p. 222–225.
23. Quinsac, A., Ribaillier, D., Elfakir, C., Lafosse, M., and Dreux, M. 1991. A new approach to the study of glucosinolates by isocratic liquid chromatography. Part 1: Rapid determination of desulfated derivatives of rapeseed glucosinolates. Journal of the Association of Official Analytical Chemists 74:932–939.
24. Brown, P.D. and Morra, M.J. 1997. Control of soil borne plant pests using glucosinolate-containing plants. Advances in Agronomy 61:167–231.
25. Hanley, A.B., Heaney, R.K., and Fenwick, G.R. 1983. Improved isolation of glucobrassicin and other glucosinolates. Journal of the Science of Food and Agriculture 34:869–873.
26. Matthiessen, J.N. and Shackleton, M.A. 2000. Advantageous attributes of larval whitefringed weevil, *Naupactus leucoloma* (Coleoptera:Curculionidae) for bioassaying soil fumigants, and responses to pure and plant-derived isothiocyanates. Bulletin of Entomological Research 90:349–355.
27. Mazzola, M., Granatstein, D.M., Elfving, D.C., and Mullinix, K. 2001. Suppression of specific apple root pathogens by *Brassica napus* seed meal amendment regardless of glucosinolate content. Disease Control and Pest Management 91: 673–679.
28. Dasberg, S. and Or, D. 1999. Drip Irrigation. Springer-Verlag, Berlin. p. 162.
29. Brown, P.D. and Morra, M.J. 1993. Fate of ionic thiocyanate (SCN^-) in soil. Journal of Agriculture and Food Chemistry 41:978–982.
30. Teyker, R.H., Hoelzer, H.D., and Liebl, R.A. 1991. Maize and pigweed response to nitrogen supply and form. Plant and Soil 135:287–292.
31. Whitson, T.D. (ed.) 1996. Weeds of the West. The Western Society of Weed Science in cooperation with the Western US. Land Grant Universities Cooperative Extension Services, Jackson Hole, WY.
32. Poudel, D.D., Horwath, W.R., and Lanini, W.T. 2002. Comparison of soil N availability and leaching potential, crop yields and weeds in organic, low-input and conventional farming systems in northern California. Agriculture, Ecosystems and Environment 90:125–137.
33. Organic Farming Research Foundation (OFRF). 1999. Third Biennial National Organic Farmers' Survey. OFRF, Santa Cruz, CA.

Renewable Agriculture and Food Systems: 22(3); 213–222 doi:10.1017/S1742170507001755

An alternative way to evaluate the environmental effects of integrated pest management: Pesticide risk indicators

Thomas J. Greitens[1,*] and Esther Day[2,*]

[1]American Farmland Trust, Center for Agriculture in the Environment, 148 N. Third Street, Dekalb, IL 60115, USA.
[2]135 Francisco Terrace, Oak Park, IL 60302, USA.
*Corresponding author: thomas.greitens@gmail.com or fripp_1@ameritech.net

Accepted 1 November 2006 **Research Paper**

Abstract

This study examines whether pesticide risk indicators can be used to evaluate the environmental effects of pesticide applications within integrated pest management (IPM) projects. Pesticide risk indicators, commonly used in European countries, are mathematical equations that consider data inputs such as application rates, toxicity levels of a pesticide's active ingredient, meteorological data, the soil characteristics of farm fields, and other information to generate potential risk scores for pesticide applications. These potential risk scores represent the best estimate of a pesticide's impact on the surrounding environment. This project analyzed eight pesticide risk indicators, developed throughout Europe and the United States, with two years of pesticide application data from four farms using IPM. This two-year study allowed for a determination of the validity and reliability of pesticide risk indicators. The findings reveal that only three pesticide risk indicators performed consistently and gave valid results. These indicators are: the synoptic evaluation model for plant protection agents (SYNOPS) indicator from Germany, the multi-attribute toxicity factor from the United States, and the environmental impact quotient from the United States. As a result, the authors recommend these three indicators for future research and for IPM evaluative efforts that emphasize the environmental effects of pesticides.

Key words: integrated pest management, pesticide risk indicators, environmental assessment, program evaluation, pesticide risk

Introduction

Consumers are increasingly concerned with how agricultural practices impact the environment[1]. This concern has translated into the growth of a variety of programs including the United States Department of Agriculture (USDA's) National Organic Program, independently certified eco-label strategies, and integrated pest management (IPM) programs. Traditionally, IPM can be defined as a systems approach that employs biological, chemical and other agricultural practices to minimize environmental, health and economic risks from agricultural pests[2,3]. To reduce those types of risks, IPM practices commonly include such things as reducing pesticide use, applying reduced risk pesticides and releasing beneficial insects into a farming area[2].

While existing as an agricultural strategy for many decades, IPM programs took on an increased level of significance in the past ten years as new programs were introduced emphasizing IPM strategies as a way to reduce the environmental impacts from pesticide use. One of these programs was the National IPM Initiative. The purpose of this initiative was to have 75% of agricultural producers implement IPM practices by the year 2000[4]. However, the General Accounting Office discovered a number of problems with this initiative and IPM programs in general. Among these problems were a lack of measurable goals for IPM programs, an absence of a methodology to measure any progress occurring in IPM programs, and inefficient management of IPM programs by the USDA and the United States Environmental Protection Agency (USEPA)[4]. From a policy perspective, this report revealed a basic deficiency in IPM programs. Without measurable goals, IPM programs could not be evaluated properly and did not conform to the Government Performance and Results Act (GPRA). In addition, no data existed to indicate that IPM techniques were better for the environment than conventional agricultural techniques. Without this type of data, IPM

© 2007 Cambridge University Press

stakeholders faced the prospect of reduced funding since policymakers would not be able to determine if resources spent on IPM programs actually achieved anything.

As a result of the GAO report, consensus has emerged on the need to evaluate the environmental benefits of IPM programs. Researchers traditionally evaluated IPM programs using 'adoption surveys' that measured how many growers in one specific area consistently used an IPM technique in their farming practices[4]. The assumption behind such surveys was that an increased level of IPM adoption equated to a decreased level of environmental risk from agricultural practices. However, IPM programs now have to quantitatively show program outcomes. One way to quantitatively show that IPM programs can reduce the environmental risk from pesticide applications is with pesticide risk indicators.

Pesticide risk indicators generate a potential environmental risk score based on certain data inputs like the amount of pesticide applied to a field, the level of toxicity of the pesticide to beneficial organisms, and the pesticide's ability to infiltrate groundwater. This potential risk score represents the amount of potential environmental impact that a pesticide application strategy causes in a particular area (since only environmental sampling can indicate if an actual environmental impact occurred, results from pesticide risk indicators are always phrased with the word potential impact). Researchers have not determined the validity or reliability of these indicators with real application data. Instead, researchers typically use estimates of pesticide application data to determine validity and reliability[5]. As a result, this study attempts to establish the validity and reliability of eight pesticide risk indicators with actual application data.

Pesticide Risk Indicators

There are two basic types of pesticide risk indicators. Those that use a ranking approach to generate potential risk scores, and those that use some combination of ranks and predicted environmental concentrations (PECs) to generate potential risk scores. In the ranking approach, the indicator establishes unitless ranks that categorize data points on the pesticide's toxicity to humans and a variety of beneficial organisms. In addition, indicators can use the ranking methodology to categorize data points that reveal how long a pesticide stays in surface water, ground water, or soil. Depending on the indicator, different equations either divide or multiply these two ranks to estimate a potential risk score for a pesticide's active ingredient. Then, by multiplying or dividing the potential risk score by the application rate, these types of indicators can generate a potential risk score for each application of a pesticide's active ingredient.

Other pesticide risk indicators rely on a more quantifiable PEC methodology to assess potential risk. In this type of methodology, the indicator uses environmental engineering equations in order to calculate how much of the pesticide remains in the soil, groundwater, surface water and even air. The indicators that use a PEC methodology often also employ a ranking approach, either to categorize the amount of the pesticide's concentration or to categorize pesticide toxicity data. By multiplying or dividing PECs by ranked data, the indicators using a PEC methodology estimate a potential risk score for a pesticide application.

Table 1. Pesticide risk indicators and their country of origin.

Pesticide risk indicator	Acronym	Country
Environmental potential risk indicator for pesticides	EPRIP	Italy
Environmental yardstick for pesticides	EYP	The Netherlands
Pesticide environmental risk indicator	PERI	Sweden
Synoptic evaluation model for plant protection agents	SYNOPS_2	Germany
System for predicting the environmental impact of pesticides	SyPEP	Belgium
Environmental impact quotient	EIQ	USA
Chemical hazard evaluation for management strategies	CHEMS 1	USA
Multi-attribute toxicity factor	MATF	USA

After reviewing the existing literature, the authors chose eight indicators to analyze because they either appeared in peer-reviewed journals or were actively used by governmental agencies and European researchers (Table 1). The design of these indicators, how they can be used, and the equations behind the indicators have all been specifically explained in previous studies[5–14]. Therefore, in consideration of space, this research will only provide a brief overview of each indicator (however, a complete overview of each indicator's equations is available at http://www.aftresearch.org/ipm/risk/equations.pdf).

EIQ: environmental impact quotient (USA)

J. Kovach, C. Petzoldt, J. Degni, and J. Tette[6] developed the EIQ indicator. EIQ is a pesticide risk indicator that assesses the potential impact of pesticides on farmworkers, consumers and terrestrial organisms. It ranks a pesticide's toxicity data to generate potential risk scores for beneficial organisms and humans. It then multiplies these potential risk scores by the pesticide's application rate to determine a final potential risk score.

CHEMS 1: chemical hazard evaluation for management strategies (USA)

M. Swanson[7] led a group of researchers who designed the CHEMS 1. CHEMS 1 is a chemical risk indicator

that considers the potential environmental impact of chemicals on air, soil, groundwater and surface water. CHEMS 1 uses a ranking approach to generate risk scores for chemical applications. For example, the indicator ranks chemical toxicity data to determine a chemical hazard value for human health and the environment. These hazard values are then multiplied by a ranked concentration factor that shows how much of the chemical already resides in the environment. To arrive at a ranked concentration factor, the indicator adds the amount of chemical applied and the amount of chemical already residing in the specific environmental area, and then ranks that resulting value. It is important to note that the design of CHEMS 1 favors industrial chemicals rather than agricultural pesticides. However, the authors decided to include it in the analysis since it uses a ranking methodology similar to other risk indicators designed exclusively for agriculture.

SYNOPS_2: synoptic evaluation model for plant protection agents (Germany)

The Federal Biological Research Centre for Agriculture and Forestry, Institute for Technology Assessment in Plant Protection, Kleinmachnow, Germany developed SYNOPS[8]. The purpose of the indicator is to assess the environmental risk potential of a pesticide application strategy in a region and to compare pest management strategies with different pesticide options. The indicator calculates PECs in soil, groundwater and surface water for each pesticide. Then, the indicator divides those values by toxicity data for beneficial organisms and humans to produce a potential risk value.

PERI: pesticide environmental risk indicator (Sweden)

C. Nilsson[9] developed the PERI indicator as part of a system of indicators that Swedish farmers could use to evaluate potential environmental risk as part of an ISO 14001 certification process. To evaluate potential environmental risk, PERI uses a ranking methodology that assesses pesticide properties and toxicity values on a 1–5 scale. Once calculated, the indicator multiplies the potential environmental risk score by the pesticide application rate to arrive at a final estimate of potential environmental risk for groundwater, surface water and air.

SyPEP: system for predicting the environmental impact of pesticides (Belgium)

L. Pussemier[10] developed the SyPEP model to help farmers, extension services and regulating agencies by providing information on the environmental impact of pesticides. The indicator calculates a long-term PEC for groundwater, a short-term PEC for groundwater, and a PEC for surface water. It then divides toxicity information by the PEC in each environmental compartment. The resulting value in each of the three compartments is then ranked on a 0–5 scale to arrive at a SyPEP score.

EYP: the environmental yardstick for pesticides (The Netherlands)

J. Reus and P. Leendertse[11] developed EYP for use by Dutch farmers and governmental officials. The EYP indicator calculates a PEC of a pesticide for groundwater, surface water and soil. The indicator then multiplies the PEC by the pesticide's toxicity data in order to produce Environmental Impact Points that reflect potential risk to beneficial organisms and humans.

EPRIP: environmental potential risk indicator for pesticides (Italy)

M. Trevisan, G. Errera, E. Capri, L. Padovani, and A. Del Re[12] developed EPRIP for Italian agriculture. EPRIP calculates and compares PECs across the environmental compartments of air, soil, groundwater and surface water. To arrive at a PEC, the indicator uses a variety of equations that consider a pesticide's exposure potential and site-specific application data. Then, EPRIP divides the PEC by the pesticide's toxicity data in order to generate an EPRIP potential risk score for beneficial organisms and humans.

MATF: multi-attribute toxicity factor model (USA)

C. Benbrook[14] led a research team that designed the MATF indicator to calculate the toxicity of pesticides for the 'Healthy Grown' Wisconsin Potato IPM Labeling Project. The MATF indicator ranks toxicity data in order to generate toxicity factor scores for beneficial organisms and humans. It then multiplies these scores by the pesticide's application rate in order to produce toxicity units for each application, with more toxicity units indicating more potential risk. It is important to note that researchers designed this indicator specifically for Wisconsin potatoes. However, the present authors included it in this analysis because its methodology is similar to the other indicators analyzed.

Method of Analysis

Building upon the results of other research, stressing the need to develop systems that can evaluate the impacts of pesticide applications[15,16], this study analyzed eight pesticide risk indicators with actual pesticide application data from four IPM farms in Southwest Florida that grew either tomatoes or peppers (Table 2). These farms were small with field acreage ranging in size from 8 ha (20 acres) for farms A, B and C, and 34 ha (85 acres) for farm D. All of the farms had sandy soil, resided near water bodies and routinely implemented advanced IPM tactics as part of their growing strategy. By analyzing these indicators with actual pesticide application data from these farms, this analysis reached a basic conclusion on the validity and reliability of these indicators.

Table 2. Crop scenarios for each farm participating in the study.

	Year 1 crop	Year 2 crop	Size (ha)
Farm A	Pepper	No crops/fallow	8
Farm B	Tomato	Pepper	8
Farm C	Pepper	Pepper	8
Farm D	Tomato	Tomato	34

As shown in Table 3, each pesticide risk indicator calculated a potential risk score based on certain input parameters. For example, all of the indicators required pesticide application data, which was obtained from four vegetable growers over two growing seasons. For these years, the growers grew either tomatoes or peppers, or left their fields fallow. In addition to pesticide application data, some of the indicators required soil data. To obtain these data, researchers used soil probes to collect the top 20 cm of topsoil from representative sites on each farm. In total, 12 soil samples were taken: five from Farm A, one from Farm B, one from Farm C, and five from Farm D. More samples were taken on Farms A and D because fields in those areas had slightly more variability in soil characteristics. In addition, more samples were taken on Farm D because of its larger size. When multiple samples were taken on a farm, researchers divided the farm into four identical rectangular quadrants and then randomly chose five locations for sample sites with at least one sample originating from each quadrant. All of these samples were then analyzed separately to determine organic content levels, pH levels, and sand/silt/clay levels. These results were then averaged for Farms A and D so that each farm had one set of soil data. As shown in Table 3, some of the indicators used this type of information to calculate the ability of a pesticide's active ingredient to leach into groundwater.

Additional information collected included the acreage size of each field, meteorological data, a field's distance to a body of water, and toxicity data for beneficial organisms. Toxicity data came from the US Environmental Protection Agency's Ecotox Database (http://www.epa.gov/ecotox/) and *The Pesticide Manual*[17]. Once collected, all of these data points allowed each pesticide risk indicator to generate a potential risk score for each farm over 2 years.

If the indicators possess validity, then high-risk pesticide applications should result in higher potential risk scores. These types of high-risk pesticide applications can include the use of high-risk active ingredients such as methyl bromide. But they can also include large applications of newer, safer pesticides since all pesticides possess some amount of toxicity. This type of basic validity, where a measure produces accurate assessments, is known as measurement validity[18].

Additionally, if the indicators possess reliability, then they should generate consistent potential risk scores across different farms and through different years. For example, two different indicators should similarly assess methyl bromide applications even as other site-specific variables change across different farms and through different years. This is known as measurement reliability, since it examines whether a measurement tool such as a pesticide risk indicator produces similar results with repeated uses[18].

Assessing this type of validity and reliability is not easy with pesticide risk indicators. As detailed in the preceding section, each indicator has a different methodology with different sets of data inputs. This makes a direct comparison of each indicator's potential risk scores meaningless. Researchers on European pesticide risk indicators associated with the Concerted Action on Pesticide Environmental Risk Indicators project (more commonly known as the CAPER project) solved this problem by ranking pesticide application rates and the potential risk scores of each indicator from highest to lowest, and then analyzing those ranks with Spearman's Rho correlations for ranked data[5].

In a Spearman's Rho correlation analysis, interval level data cases are ranked on an ordinal scale from highest to lowest with tied data cases resulting in averaged ranks. This results in ranked data for each variable of interest. After ranking each variable's data cases, the ranked results between each variable of interest can be analyzed with Spearman's Rho correlations to determine if there is a statistically significant correlation between the ranks of one variable and the ranks of another variable. This type of analysis helped CAPER researchers determine if different pesticide risk indicators from Europe assessed the same application strategy similarly. Building upon the results of the CAPER project, such an analysis will also be performed in this project to help assess measurement validity and reliability for both European and American pesticide risk indicators.

When the application rate of the pesticide's active ingredient and the potential risk score from each indicator are ranked in such a manner, a determination of validity can

Table 3. Required data inputs for each pesticide indicator.

	EPRIP	EYP	PERI	SYNOPS_2	SyPEP	EIQ	CHEMS 1	MATF
Pesticide application rate	•	•	•	•	•	•	•	•
Toxicity to beneficials	•	•	•	•	•	•	•	•
Organic content of soil	•	•		•				
Weather data	•	•		•	•			
Distance to water bodies	•			•	•			

Table 4. Total ranked scores for farms in year 1 (with tied ranks averaged according to Spearman's Rho analytic protocol[19]).

Active ingredients (a.i.)	Rate	CHEMS 1	EIQ	EPRIP	EYP	MATF	PERI	SYNOPS_2	SyPEP
Farm A									
Methyl bromide	1	7	1	1	2	1	1	3	2
Chloropicrin	2	5	2	2	6	2	4	2	8.5
Maneb	3	8	4	4.5	7	3	9	4	8.5
Copper hydroxide	4	6	3	7	1	4	6	1	2
Methomyl	5	2	5	3	4	6	5	5	4
Metolachlor	6	4	7	8.5	9	8	7	6	6.5
Glyphosate	7	11	6	6	3	7	10	9	10
Tebufenozide	8	9	8	10	10	10	8	8	6.5
Cyfluthrin	9	1	9	8.5	5	5	3	7	2
Abamectin	10	3	10	4.5	8	9	2	10	5
Spinosad	11	10	11	11	11	11	11	11	11
Farm B									
Copper hydroxide	1	4	1	8	1	1	4	2	1
Endosulfan	2	1	2	1	2	2	7	1	3
Maneb	3	6	3	3	3	4	8	4	6
Chlorothalonil	4	3	4	2	6	5	6	3	3
Dimethoate	5	2	5	6	7	3	5	5	7
Tebufenozide	6	7	6	6	8	8	2	7	5
Mefenoxam	7	8	7	6	5	6	1	8	8
Azoxystrobin	8	5	8	4	4	7	3	6	3
Farm C									
Maneb	1	5	1	1	2	1	7	2	4.5
Copper hydroxide	2	4	2	7	1	2	4	1	1
Oxamyl	3	3	4	3	5	4	2	5	4.5
Dimethoate	4	1	3	5	7	3	3	3	7
Methomyl	5	2	6	2	3	6	5	6	2
Tebufenozide	6	6	5	5	6	7	6	4	3
Mefenoxam	7	7	7	5	4	5	1	7	6
Farm D									
Methyl bromide	1	9	1	2	3	1	1	3	1.5
Copper hydroxide	2	4	2	7	1	2	7	1	1.5
Mancozeb	3	6	3	4	9	3	11	4	11
Chlorothalonil	4	3	4	3	5	4	10	2	6.5
Paraquat dichloride	5	5	5	5	2	5	14	6	10
Methomyl	6	2	9	8	4	10	6	8	3
Imidacloprid	7	11	6	10.5	8	6	3	9	12
Cyromazine	8.5	14	7	13	13	12	5	12	6.5
Tebufenozide	8.5	8	8	10.5	12	14	2	10	6.5
Metribuzin	10	12	10	13	11	9	12	13	9
Spinosad	11	10	11	6	14	8	4	11	13
Esfenvalerate	12	1	13	1	6	7	9	5	6.5
Mefenoxam	13	13	12	13	7	13	13	14	14
Abamectin	14	7	14	9	10	11	8	7	6.5

occur since the ranked potential risk scores should correlate with the ranked application rates (i.e. higher potential risk scores should correlate with higher risk application rates). This type of Spearman's Rho correlation analysis can also help determine reliability since statistically significant Spearman's Rho correlations between one indicator's ranked potential risk scores and another indicator's ranked potential risk scores should remain as pesticide application strategies change from farm to farm and from year to year. For example, if the EIQ and MATF indicators reliably generate potential risk scores that correlate with one another, then that correlation should remain across different farms and through different years. This helps to determine if the indicators possess measurement reliability.

Results

Establishing validity

We performed this methodology on each indicator, for each farm, for 2 years. Basic conclusions on validity became apparent without even using the Spearman's Rho analysis. As shown in Tables 4 and 5, most indicators gave higher

Table 5. Total ranked scores for farms in year 2 (with tied ranks averaged according to Spearman's Rho analytic protocol[19]).

Active Ingredients (a.i.)	Rate	CHEMS 1	EIQ	EPRIP	EYP	MATF	PERI	SYNOPS_2	SyPEP
Farm A (left fallow)	–	–	–	–	–	–	–	–	–
Farm B									
Methyl bromide	1	4	1	1	2	1	1	2	1.5
Maneb	2	6	2	2.5	3	2	7	3	5.5
Copper hydroxide	3	3	3	6	1	5	6	1	1.5
Oxamyl	4	2	5	2.5	4	3	5	4	5.5
Dimethoate	5	1	4	5	6	4	4	5	7
Tebufenozide	6	5	6	4	5	8	3	6	3.5
Imidacloprid	7.5	7	8	7.5	7	7	8	7	8
Thiamethoxam	7.5	8	7	7.5	8	6	2	8	3.5
Farm C									
Methyl bromide	1	4	1	1.5	2	1	1	3	1.5
Maneb	2	5	2	3	3	2	6	4	6
Copper hydroxide	3	3	3	6	1	4	7	2	1.5
Endosulfan	4	1	4	1.5	4	5	3	1	5
Dimethoate	5	2	5	4.5	7	3	4	5	7
Tebufenozide	6	6	6	4.5	6	8	5	6	3.5
Imidacloprid	7	7	8	7.5	5	7	8	7	8
Thiamethoxam	8	8	7	7.5	8	6	2	8	3.5
Farm D									
Methyl bromide	1	9	1	1.5	3	1	1	2	1.5
Copper hydroxide	2	3	2	9	1	2	4	1	1.5
Mancozeb	3	6	3	4	7	3	9	5	10
Chlorothalonil	4	2	4	3	4	4	10	4	3.5
Paraquat dichloride	5	8	5	5	2	5	13	6	8.5
Buprofezin	6	13	8	11.5	13	13	11	12	8.5
Endosulfan	7	1	6	1.5	5	6	8	3	5
Metribuzin	8	12	9	13	8	7	6	9	6.5
Clethodim	9	4	10	7	14	9	5	14	13.5
Tebufenozide	10	10	7	11.5	10	11	7	7	6.5
Spinosad	11	11	11	7	12	8	3	8	12
Pyriproxyfen	12	5	13	10	9	12	2	10	11
Mefenoxam	13	14	12	14	6	10	14	13	13.5
Indoxacarb	14	7	14	7	11	14	12	11	3.5

potential risk scores to higher risk pesticide applications that included active ingredients in restricted use pesticides, organophosphates and carbamates. The highest potential risk scores generally went to methyl bromide applications. This indicates at least a rudimentary level of measurement validity: the pesticide risk indicators gave higher potential risk scores to higher risk pesticide applications.

However, the best evidence for validity is from the Spearman's Rho correlation analysis with ranked application rates and ranked potential risk scores. If these indicators measure the potential risk of pesticides correctly, then larger application rates should result in larger potential risk scores. That would result in statistically significant correlations between the ranked potential risk score of each indicator and the application rate. As detailed in Tables 6 and 7, most of the indicators had a statistically significant correlation with the application rate on at least one farm. However, only EIQ, MATF and SYNOPS had statistically significant correlations on each farm throughout the 2 years of application data. This reveals that these indicators possess the most measurement validity since they had constant, statistically significant correlations with the application rate across different farms, application strategies and different years.

Establishing reliability

Tables 6 and 7 also reveal conclusions on measurement reliability. These tables show that significant correlations between many pesticide risk indicators are not consistent from year to year or even from farm to farm. This indicates that certain pesticide risk indicators do not generate reliable potential risk scores. For reliability, we would expect to find that significant correlations between pesticide risk indicators would remain from farm to farm and from year to year, even though pesticide application strategies changed. Instead, we find that significant correlations between many of the indicators disappear and reappear when the analysis shifts to new farms or new years that have different pesticide application strategies.

Table 6. Spearman's Rho correlations for Farms A–D, year 1.

	Rate	CHEMS 1	EIQ	EPRIP	EYP	MATF	PERI	SYNOPS_2
Farm A								
CHEMS 1	0.00900							
EIQ	0.982**	−0.0360						
EPRIP	0.740**	0.247	0.740**					
EYP	0.582	0.145	0.691*	0.571				
MATF	0.882**	0.200	0.882**	0.753**	0.709*			
PERI	0.300	0.709*	0.300	0.598	0.400	0.491		
SYNOPS	0.900**	0.227	0.900**	0.562	0.618	0.855**	0.364	
SyPEP	0.244	0.645*	0.272	0.259	0.562	0.401	0.765**	0.452
Farm B								
CHEMS 1	0.524							
EIQ	0.976**	0.500						
EPRIP	0.122	0.415	0.122					
EYP	0.619	0.238	0.690	0.122				
MATF	0.857**	0.667	0.905**	0.000	0.667			
PERI	−0.667	−0.619	−0.643	−0.659	−0.381	−0.571		
SYNOPS	0.881**	0.786*	0.857**	0.415	0.643	0.810*	−0.762*	
SyPEP	0.488	0.439	0.415	0.125	0.537	0.342	−0.220	0.683
Farm C								
CHEMS 1	0.321							
EIQ	0.929**	0.250						
EPRIP	0.259	0.148	0.074					
EYP	0.500	−0.214	0.321	0.111				
MATF	0.857*	0.179	0.857*	0.074	0.464			
PERI	−0.393	−0.0360	−0.464	−0.408	−0.286	−0.107		
SYNOPS	0.786*	0.179	0.929**	−0.222	0.321	0.714	−0.500	
SyPEP	0.216	−0.0360	0.0900	−0.112	0.631	−0.126	−0.450	0.270
Farm D								
CHEMS 1	0.306							
EIQ	0.968**	0.121						
EPRIP	0.450	0.720**	0.347					
EYP	0.590*	0.596*	0.490	0.493				
MATF	0.772**	0.402	0.741**	0.723**	0.618*			
PERI	0.176	−0.156	0.187	0.0130	−0.222	−0.0150		
SYNOPS	0.689**	0.741**	0.613*	0.804**	0.684**	0.810**	0.0370	
SyPEP	0.446	0.468	0.342	0.299	0.452	0.257	−0.385	0.569*

* Correlation is significant at the 0.05 level (two-tailed).
** Correlation is significant at the 0.01 level (two-tailed).

These inconsistencies make a final interpretation on reliability difficult. Perhaps the best interpretation of the data is that the rankings of potential pesticide risk from the indicators SYNOPS, EIQ and MATF generally correlate with each other at statistically significant levels. In contrast, the other indicators do not have consistent correlations. As a result, this study's results indicate that these three pesticide risk indicators have the most measurement reliability. That is, the ranked values of potential risk scores correlate fairly consistently with these three indicators from different farms over different years.

Discussion

Using pesticide risk indicators to evaluate IPM programs has certain advantages. Perhaps most importantly, using these indicators to evaluate IPM programs allows policymakers and stakeholders to determine if IPM programs actually reduce the environmental and health risks from pesticide use. However, there are also disadvantages to using these indicators. Currently, there is disagreement in the toxicology literature regarding the most effective method to measure environmental and health impacts from agricultural chemical applications. The literature recognizes that agricultural operations can result in negative environmental impacts and pose some risk to human health[20]. Yet, no agreed upon methodology exists to measure these impacts. For example, methods for measuring the environmental effects of pesticide use include hazard indicators that assess environmental effects by analyzing chemical property data associated with a particular pesticide and methods that attempt to predict

Table 7. Spearman's Rho correlations for Farms B–D, year 2.

	Rate	CHEMS 1	EIQ	EPRIP	EYP	MATF	PERI	SYNOPS_2
Farm B								
CHEMS 1	0.443							
EIQ	0.970**	0.452						
EPRIP	0.812*	0.422	0.747*					
EYP	0.898**	0.452	0.833*	0.627				
MATF	0.850**	0.381	0.833*	0.747*	0.571			
PERI	0.096	0.0710	0.190	0.289	−0.0480	0.143		
SYNOPS	0.922**	0.548	0.881**	0.602	0.976**	0.667	−0.0710	
SyPEP	0.470	0.0240	0.485	0.276	0.594	0.182	0.582	0.509
Farm C								
CHEMS 1	0.571							
EIQ	0.976**	0.548						
EPRIP	0.764*	0.655	0.764*					
EYP	0.833*	0.405	0.762*	0.436				
MATF	0.833*	0.476	0.857**	0.582	0.524			
PERI	0.143	0.143	0.286	0.473	−0.214	0.333		
SYNOPS	0.786*	0.857**	0.762*	0.727*	0.762*	0.524	−0.0950	
SyPEP	0.386	0.0600	0.494	0.202	0.446	0.205	0.422	0.349
Farm D								
CHEMS 1	0.314							
EIQ	0.960**	0.323						
EPRIP	0.529	0.642*	0.542*					
EYP	0.613*	0.319	0.684**	0.376				
MATF	0.846**	0.371	0.868**	0.593*	0.763**			
PERI	0.200	0.209	0.165	0.150	−0.0460	0.284		
SYNOPS	0.745**	0.481	0.833**	0.617*	0.776**	0.815**	0.301	
SyPEP	0.515	0.347	0.559*	0.390	0.546*	0.418	0.133	0.716**

* Correlation is significant at the 0.05 level (two-tailed).
** Correlation is significant at the 0.01 level (two-tailed).

the actual environmental concentration of the pesticide in the environment[21]. Consequently, choosing one environmental assessment method over another becomes a complex process that often depends on which environmental threat the evaluators, stakeholders or policymakers wish to assess.

When choosing pesticide risk indicators for IPM evaluation, evaluators, stakeholders and policymakers should analyze how the pesticide risk indicator actually generates potential risk scores. In this analysis, the most consistent pesticide risk indictors (SYNOPS, EIQ and MATF) all differ in terms of methodology. When compared to the MATF and EIQ indicators, the SYNOPS indicator is more complex. It considers daily weather information and specific soil information while the MATF and EIQ indicators do not. The SYNOPS indicator also predicts environmental concentrations of the pesticide used in soil, air, surface water and groundwater. In contrast, indicators like EIQ and MATF categorize data points with a ranking methodology to arrive at a potential risk score. Therefore, if an evaluator needs an actual prediction of environmental concentration (PEC) for part of an IPM evaluation, then indicators like SYNOPS have to be used.

These types of issues comprise the main concerns over using any pesticide risk indicators in IPM policy. Evaluators can use any pesticide risk indicator as part of an overall approach to evaluate an IPM growing strategy. However, based on this analysis, we recommend that evaluators use the EIQ, MATF or SYNOPS indicators. Additionally, we recommend that evaluators or researchers validate the results of these indicators with actual environmental samples. Only then, can we be sure that pesticide risk indicators generate accurate potential risk scores for pesticide applications.

Conclusion

In many cases, the pesticide risk indicators analyzed are either used by governmental agencies or by farming groups to assess environmental impact from pesticide applications[5,14]. However, in order to achieve a fully integrated approach to assessing IPM programs, a variety of other components have to be assessed other than pesticide use. Such things as nutrient management as well as the economic costs of switching to reduced risk must be included when policymakers or agricultural professionals attempt to measure the impact of IPM programs. As a result, the importance of these indicators is in their ability to contribute to a comprehensive risk assessment for IPM practices.

Researchers need to place more emphasis on interdisciplinary assessments of the economic, environmental and human health impacts of agricultural programs such as IPM. In general, IPM researchers have not included such an assessment in their work. In addition, since the passing of GPRA, there is a growing demand by the public as well as government to be socially and economically accountable for all publicly funded research. Under increased funding constraints, IPM programs must show that IPM techniques result in less environmental risk. Pesticide risk indicators can help that occur. But this research shows that these indicators, as currently devised, need more scrutiny. Future analyses should examine how specific data inputs influence a pesticide risk indicator's potential risk score. In addition, researchers must determine if potential risk scores heavily influenced by application rates actually give usable information on how the pesticide application scheme is affecting the environment, or whether such scores are just an extension of the qualitative scheme that equated reduced application rates of pesticide with reduced environmental risk. Lastly, future research has to examine the economic effects of reducing environmental risk. Using pesticide risk indicators to measure environmental risk means nothing if the grower has no incentive to reduce risk in the first place.

Acknowledgements. Support for this study was provided by the US Environmental Protection Agency and American Farmland Trust.

References

1 Potter, C. 1998. Against the Grain: Agri-environmental Reform in the United States and the European Union. CAB International, New York.

2 Cuperus, G., Mulder, P., and Royer, T. 2000. Implementation of ecologically-based IPM. In J. Rechcigl and N. Recheigl (eds). Insect Pest Management: Techniques for Environmental Protection. Lewis Publishers, Boca Raton, FL. p. 171–204.

3 Zalom, F. 2001. Pesticide use practices in integrated pest management. In R. Krieger (ed.). Handbook of Pesticide Toxicology. 2nd ed. Academic Press, San Diego, CA. p. 275–283.

4 General Accounting Office. 2001. Agricultural Pesticides: Management Improvements Needed to Further Promote Integrated Pest Management. Report No. GAO-01-815. General Accounting Office, Washington, DC.

5 Reus, J., Leendertse, P., Bockstaller, C., Fomsgaard, I., Gutsche, V., Lewis, K., Nilsson, C., Pussemier, L., Trevisan, M., van der Werf, H., Alfarroba, F., Blumel, S., Isart, J., McGrath, D., and Seppala, T. 2002. Comparison and evaluation of eight pesticide environmental risk indicators developed in Europe and recommendations for future use. Agriculture, Ecosystems, and Environment 90:177–187.

6 Kovach, J., Petzoldt, C., Degni, J., and Tette, J. 1992. A method to measure the environmental impact of pesticides. New York's Food and Life Sciences Bulletin 139:1–8.

7 Swanson, M., Davis, G., Kincaid, L., Schultz, T., Bartmess, J., Jones, S., and George, E. 1997. A screening method for ranking and scoring chemicals by potential human health and environmental impacts. Environmental Toxicology and Chemistry 16:372–383.

8 Gutsche, V. and Rossberg, D. 1999. Synoptisches bewertungsmodell furpflanzenschutzmittel (SYNOPS). In J. Reus, P. Leendertse, C. Bockstaller, I. Fomsgaard, V. Gutsche, K. Lewis, C. Nilsson, L. Pussemier, M. Trevisan, H. van der Werf, F. Alfarroba, S. Blümel, J. Isart, D. McGrath, and T. Seppala (eds). Comparing Environmental Risk Indicators for Pesticides: Results of the European CAPER Project. Centre for Agriculture and the Environment, Utrecht, The Netherlands. p. 236–257.

9 Nilsson, C. 1999. PERI. In J. Reus, P. Leendertse, C. Bockstaller, I. Fomsgaard, V. Gutsche, K. Lewis, C. Nilsson, L. Pussemier, M. Trevisan, H. van der Werf, F. Alfarroba, S. Blümel, J. Isart, D. McGrath, and T. Seppala (eds). Comparing Environmental Risk Indicators for Pesticides: Results of the European CAPER Project. Centre for Agriculture and the Environment, Utrecht, The Netherlands. p. 121–124.

10 Pussemier, L. 1999. A system for predicting the environmental impact of pesticides in Belgium. In J. Reus, P. Leendertse, C. Bockstaller, I. Fomsgaard, V. Gutsche, K. Lewis, C. Nilsson, L. Pussemier, M. Trevisan, H. van der Werf, F. Alfarroba, S. Blümel, J. Isart, D. McGrath, and T. Seppala (eds). Comparing Environmental Risk Indicators for Pesticides: Results of the European CAPER Project. Centre for Agriculture and the Environment, Utrecht, The Netherlands. p. 131–138.

11 Reus, J. and Leendertse, P. 1999. The environmental yardstick for pesticides (field crops). In J. Reus, P. Leendertse, C. Bockstaller, I. Fomsgaard, V. Gutsche, K. Lewis, C. Nilsson, L. Pussemier, M. Trevisan, H. van der Werf, F. Alfarroba, S. Blümel, J. Isart, D. McGrath, and T. Seppala (eds). Comparing Environmental Risk Indicators for Pesticides: Results of the European CAPER Project. Centre for Agriculture and the Environment, Utrecht, The Netherlands. p. 59–68.

12 Trevisan, M., Errera, G., Capri, E., Padovani, L., and Del Re, A.A.M. 1999. Environmental potential risk indicator for pesticides. In J. Reus, P. Leendertse, C. Bockstaller, I. Fomsgaard, V. Gutsche, K. Lewis, C. Nilsson, L. Pussemier, M. Trevisan, H. van der Werf, F. Alfarroba, S. Blümel, J. Isart, D. McGrath, and T. Seppala (eds). Comparing Environmental Risk Indicators for Pesticides: Results of the European CAPER Project. Centre for Agriculture and the Environment, Utrecht, The Netherlands. p. 141–147.

13 Day, E. and Greitens, T. 2002. Environmental Indicators Results. Center for Agriculture in the Environment, Dekalb, IL.

14 Benbrook, C., Sexon, D., Wyman, J., Stevenson, W., Lynch, S., Wallendal, J., Diercks, S., Van Haren, R., and Granadino, C. 2002. Developing a pesticide risk assessment tool to monitor progress in reducing reliance on high-risk pesticides. American Journal of Potato Research 79:183–199.

15 Sorenson, A. 1994. Proceedings of the National Integrated Pest Management Forum. Center for Agriculture in the Environment, Dekalb, IL.

16 Lynch, S., Greene, C., and Kramer-LeBlanc, C. 1997. The Third National IPM Symposium/Workshop: broadening support for 21st century IPM. In S. Lynch, C. Greene, and C. Kramer-LeBlanc (eds). Proceedings of the Third National IPM Symposium/Workshop. USDA–Economic Research Service

(ERS) Miscellaneous Publication No. 1542. USDA–ERS, Washington, DC. p. 1–3.
17 Tomlin, C. 2000. The Pesticide Manual, 12th ed. British Crop Protection Council, Farnham, Surrey, UK.
18 Hatry, H. and Newcomer, K. 2004. Pitfalls of evaluation. In J. Wholey, H. Hatry, and K. Newcomer (eds). Handbook of Practical Program Evaluation. 2nd ed. John Wiley and Sons, San Francisco, CA. p. 547–570.
19 Chen, P. and Popovich, P. 2002. Correlation: Parametric and Nonparametric Measures. Sage Publications, Thousand Oaks, CA.
20 Ruhl, J.B. 2000. Farms, their environmental harms, and environmental law. Ecology Law Quarterly 27:263–349.
21 Falconer, K. 2002. Pesticide environmental indicators and environmental policy. Journal of Environmental Management 65:285–300.

Renewable Agriculture and Food Systems: 22(3); 223–232 doi:10.1017/S1742170507001780

Farm-gate nutrient balance assessment of organic dairy farms at different intensity levels in Germany

G. Haas*, C. Deittert, and U. Köpke

Institute of Organic Agriculture, University of Bonn, Katzenburgweg 3, D-53115 Bonn, Germany.
*Corresponding author: iol@uni-bonn.de

Accepted 18 November 2006 **Research Paper**

Abstract

Organic farms are characterized as low external input agro-ecosystems. Currently, some organic dairy farmers feed higher amounts of concentrates and succulent feed, some of which is purchased, to increase the dairy performance of their cows. To assess the environmental impact of this practice, nutrient balances at the farm-gate level of 26 organic dairy farms located in two different regions in Germany were compiled and analysed. The farms are characterized by different production features and feeding intensity levels [0–2.72 t dry matter (DM) of concentrates per cow and year, which was 0–378 g kg^{-1} milk] yielding 5150–8790 kg milk on average per cow and year. The area- and product (milk)-related farm-gate nutrient budgets for P and K are almost balanced [mean −3 kg P ha^{-1}, range (R): −14 to 4 kg P ha^{-1}; −0.5 g P kg^{-1} milk, R: −2.8 to 0.9 g P kg^{-1} milk and 1 kg K ha^{-1}, R: −13 to 15 kg K ha^{-1}; 0.1 g K kg^{-1} milk, R: −2.4 to 3.9 g K kg^{-1} milk]. The N surplus averages only 43 kg ha^{-1} (R: 8–85 kg N ha^{-1}) and 8.2 g kg^{-1} milk (R: 2.1–17.1 g kg^{-1} milk), but the correlation between the amount of feed purchased on a net basis and N surplus is significant ($r = 0.56$, $P = 0.003$). Average area-related nutrient use efficiency for all farms calculated as the proportion of input to output is high for N (45%), P (164%) and K (91%). The share of nutrient input and output components and correlations between parameters are presented. To classify the results, investigations comparing organic and conventional dairy farming in Europe are listed, indicating an N surplus for organic farms, which is often only half or a third of the surplus of conventional farms. However, intensification in organic dairy farming has, in some cases, significant impacts that need to be assessed to determine its environmental performance and profile.

Key words: nutrient balance, nutrient budget, dairy farm, farm gate, nitrogen, organic farming, phosphorus, potassium

Introduction

Organic farming is characterized as a low external input agro-ecosystem. More than 80% of the organic farmers in Germany are livestock producers running a mixed farming system where ruminants, particularly cattle, dominate[1]. Among other inputs, all feed should come from the farm itself or be produced within the region[2]. In conventional farming, it is common practice to purchase feed for animals in substantial amounts, whereas in organic agriculture the aim is self-sufficiency. However, because of economic pressure, mainly due to declining milk prices, conventional as well as organic dairy farmers in Germany are currently putting more and more effort into increasing the annual milk yield per cow. Since the market prices for organically produced cereals have been significantly lower for several years compared to previous organic grain prices >10 years ago, it has become attractive for organic dairy farmers to feed higher amounts of concentrates and also succulent feed (e.g. processing by-products), of which some is purchased, to improve the dairy performance of their farms (kg milk per cow). Some farms now show a performance level similar to that of well managed conventional farms.

Environmentally and ecologically sound production in line with public opinion and expectation is seen as an essential feature of organic agriculture. Because intensification of conventional agricultural production processes has led to environmental burdens (e.g. eutrophication and pollution of soil and water resources) a similar trend in organic farming, which might weaken its environmental performance, is being debated and needs to be assessed.

Farm nutrient budgets have become a central tool for assessing and reducing the environmental impact of

© 2007 Cambridge University Press

Table 1. Characteristics of analyzed dairy farms [mean, coefficient of variation (%) in parentheses, range underneath].

	Farmed area (ha)	Proportion of grassland[1] (%)	Herd size (no. of dairy cows)	Stocking[2] rate (LU ha^{-1})	Annual milk yield[3] (kg cow^{-1})
All farms	81 (70)	69 (25)	59 (46)	1.35 (25)	6737 (14)
$n = 26$	25–320	31–100	25–153	0.77–1.96	5150–8790
NRW	116 (59)	52 (19)	71 (45)	1.14 (26)	7218 (13)
$n = 12$	63–320	31–88	42–153	0.77–1.77	5300–8790
Allgaeu	53 (43)	83 (20)	48 (35)	1.55 (17)	6325 (12)
$n = 14$	25–109	42–100	25–75	1.06–1.96	5150–7460

[1] Almost all of it permanent grassland.
[2] LU, livestock unit (each 500 kg live weight) including replacement stock.
[3] Standardized fat and protein corrected milk (FPCM) with 4.0% fat and 3.4% protein which is very close to average.

intensive farming and serve as indicators of sustainable land management[3–6]. Nutrient budgets of 30 organic farms calculated by researchers in different regions in Germany more than 10–15 years ago indicated balances for N, P and K often close to zero or even negative[7].

In this paper, the nutrient budgets at farm-gate level are analyzed for 26 organic dairy farms in two different regions in Germany to assess the environmental impact of intensified feeding through the purchase of higher amounts of feed. Nutrient budgets of these farms are part of a research project in which several indicators covering milk yield and productivity, feed components and rations, economic performance and farmers' opinions were investigated[8,9].

Materials and Methods

Regional characteristics

The 26 dairy farms in this study converted to organic agriculture between 1981 and 2000 and are located in two different German states (Bundeslaender). In North Rhine Westphalia (NRW), close to the Dutch border in northwest Germany, seven farms are located in the more or less flat lowland [10–70 m above sea level (a.s.l.)] and five farms in the hilly regions in the southern part of the state (180–370 m a.s.l.), where the proportion of permanent grassland is high. Mean precipitation at these 12 farms is 837 l m^{-2} [range (R): 600–1100 l m^{-2}] and annual mean temperature is 8.3°C (R: 7.5–9.4°C). In the state of Baden-Wuerttemberg in southwest Germany, 14 farms in the subalpine, sometimes hilly region (550–850 m a.s.l.), called Allgaeu, were analyzed. The annual mean temperature is 7.2°C (R: 6.1–8.0°C) and mean precipitation 1029 l m^{-2} (R: 800–1600 l m^{-2}), which favors the intensive use of permanent grassland.

Selection of farms

The farms were selected following suggestions made by the regional organic dairy advisers. The advisers recommended well managed (to exclude low productivity due to low management skills) full-time dairy farms, which were in close contact with the extension service and possessed a good database and accounting system. These farms were considered to have a long-term farming perspective and to represent typical examples of full-time organic dairy farming.

Farm survey and interviews

Between autumn 2002 and spring 2003, interviews took place on the farms after checking the single-farm analyses of the extension service and the farm and dairy cow records, accounts and tax sheets. The questionnaire covered all basic agricultural production data on farm structure and main dairy and forage production processes on a long-term basis. Farmers were interviewed during an intensive farm visit of about 2–3 h. Data were evaluated and cross checked, and the farmer and his extension agent were contacted if necessary.

Farm characteristics

On the farms in NRW, the dairy breed black and white Holstein Friesian dominates (64%) followed by the red and white Holstein Friesian (27%). In the Allgaeu region, Brown Swiss (54%), black and white Holstein Friesian (28%) and Simmental (11%) are the main breeds. In both regions, the cubicle housing system is predominant. Therefore, the amount of straw needed for bedding is low; however, pure-grassland farms and farms that do not cultivate cereals still need to purchase additional straw. NRW farms show a higher milk yield and are bigger in terms of area and herd size, while the share of grassland and livestock density is lower (Table 1).

Modeling of forage yield and feeding pattern

The exact forage yield and share of legumes were normally not known by the farmer. Assumptions had to be made based on intensive cross checking of the feeding ration related to performance and possible maximum intake balanced with the possible supply (yield multiplied by area per crop) according to site conditions (for details see Haas et al.[9]). In addition, assessments by extension agents and

cooperating scientists and data derived from previous on-farm investigations on some of these farms were considered.

Forage and feed production

Permanent grassland was cut for indoor green feeding, ensiling, hay or grass drying for pellets, or grazed up to five times a year [mean gross yield 8.8 t dry matter (DM) ha^{-1}]. Grass/red clover (mean gross yield 10.8 t DM ha^{-1}) and cereals (mean yield 3.6 t DM ha^{-1}) were cultivated on most of the farms. Grain cereals (wheat, oat, rye, triticale, barley, spelt) were produced for feeding and sometimes also sold as cash crops for human consumption. Pulses for feeding (faba beans, peas) cropped on some farms yielded about 3.2 t DM ha^{-1}. Potatoes were only grown in NRW (mean yield 20 t fresh matter ha^{-1}). Maize for silage (mean gross yield 12 t DM ha^{-1}) was grown on eight farms in NRW and four farms in the Allgaeu region. In general, the purpose of cereal and potato production varied according to the market quality, which determined whether the produce was used for feeding or sold. Depending on whether pre-crop effects of legumes and a sufficient amount of slurry or manure led to an adequate nitrogen supply ensuring a good baking quality, the produced cereals were sometimes sold to mills and bakeries while at the same time lower-quality cereals for feeding were purchased from other organic farms.

Milk yield and feeding

To calculate the proportion of milk from the different types of feed on an energy basis [MJ net energy for lactation (NEL)], the feeding for maintenance was allocated to all feed types being fed (Haas et al.[9]). The mean total milk yield (Table 1) was derived from roughage (74%, R: 48–89%), concentrates and dried grass pellets (23%, R: 9–48%), and succulent feeds (3%, R: 0–9%), which were predominantly commercial processing by-products (e.g. brewery grain and fruit residues). Nine of the Allgaeu farms were not allowed to feed any silage, because they delivered their milk to a dairy where the typical hard cheese of the region was produced. These farms instead fed hay and often grass pellets in winter.

Per cow and year, 0.94 t DM of concentrates (cereals, pulses, oilseed cakes) were fed (R: 0–2.72 t DM), which was 135 g kg^{-1} milk (R: 0–378 g kg^{-1}). On average, about 67% of the sum of concentrates and processing by-products was purchased. There was a relationship between the amount of purchased feed and the milk performance ($r = 0.53$, $P = 0.057$). From concentrates and succulent feed, 1471 kg milk cow^{-1} yr^{-1} (R: 50–3724 kg) were produced. The area-related productivity was almost 7000 kg milk ha^{-1}. For feed production, 0.96 ha per cow was needed, of which 0.85 ha was farm land for home-grown feed. The equivalent area for the production of the purchased feed was 0.11 ha (excluding commercial processing by-products).

Table 2. Schema of extended (including N_2 fixation) farm-gate nutrient budget.

Input	Output
Symbiotic N_2 fixation of legume crops	Livestock produce (milk, animals)
Purchase of feed	Crops (cash crops, forage)
Cattle, fertilizer, seed potatoes, straw for bedding	

Nutrient budgets

The nutrient balances for nitrogen (N), phosphorus (P) and potassium (K) at farm-gate level were compiled by considering the perennial average. Results are expressed for a single farm as one unit on an annual basis. Budgets were set up by calculating all essential inputs and outputs (Table 2).

The amount of N fixed by the forage legume crops was assessed by the gross yield of the crops and, if grown in mixtures, the share of legumes. The proportion of DM yield for grass/red clover and white clover in permanent grassland was uniformly assumed to be 75 and 15%, respectively.

Based on investigations by Boller and Noesberger[10], extended and updated by Boller et al.[11] and Weissbach[12], 30 kg N t^{-1} DM of clover yield was assumed in calculations to assess the symbiotic N_2-fixation input rate. Based on investigations by Haas[13], a uniform 75 kg N ha^{-1} was assumed to be symbiotically fixed by mixtures of hairy vetch with winter rye or of crimson clover and Italian ryegrass. For pulses, an assumption based on field trials by Köpke[14,15] was used, which considers the amount of fixed N to be similar to the grain-N yield. Though these calculations are based on several assumptions, this is a widely used method for calculating the amount of N fixed by legume cropping in Germany at the farm-gate level.

The nutrient inputs via purchased feed and straw and the nutrient outputs via sold milk, bull calves, heifers, cull cows, cash crops and feed (very rare) were calculated by the mass of each product multiplied by the nutrient content derived from regional organic on-farm research and extension-service databases (mainly for forage) and from national statistics[16]. Data for the amount of purchased feed and straw and the number of purchased or sold cattle were taken from the bookkeeping records. Apart from stock bulls every second or third year, no other livestock was bought. Only three of the 26 farms do not raise their own breeding cattle, rather they cooperate closely with another organic farm. In these cases, calves were considered as output and the replacement heifers were imported again before calving.

Seed for cereals, pulse and forage crops were generally negligible, because they usually sum up to less than 1 kg nutrient ha^{-1} of the total farm area, whereas seed potatoes were calculated based on 0.6 t DM ha^{-1}. No relevant P- or

Table 3. Annual area related farm-gate nutrient budget (kg ha^{-1} farmed area) [rounded mean, coefficient of variation (%) in parentheses, range underneath].

	N			P			K		
	Input	**Output**	**Balance**	**Input**	**Output**	**Balance**	**Input**	**Output**	**Balance**
All farms	78 (29)	35 (22)	43 (51)	4.4 (67)	7.2 (33)	−2.8 (129)	10.3 (64)	9.4 (38)	0.8 (905)
$n = 26$	43–125	20–51	8–85	0–10	4–16	−14 to 4	0–20	5–21	−13 to 15
NRW	79 (29)	33 (28)	45 (48)	4.4 (53)	6.6 (27)	−2.3 (105)	9.1 (61)	9.9 (45)	−0.8 (851)
$n = 12$	43–125	20–51	8–82	1–10	4–10	−6 to 1	2–20	5–21	−13 to 10
Allgaeu	77 (30)	37 (17)	40 (55)	4.4 (79)	7.7 (36)	−3.2 (137)	11.3 (66)	9.1 (30)	2.2 (364)
$n = 14$	50–115	23–50	13–85	0–10	5–16	−14 to 4	0–20	5–17	−8 to 15

K-containing mineral feed was bought, just pure salt licks. Except for one farm that purchased K-fertilizer, no other farm used mineral fertilizer.

Atmospheric-N deposition, nitrate leaching and denitrification were not calculated. Also accumulation and depletion of nutrients in the soil were not calculated by assuming dynamic equilibrium, but should be considered by interpreting single-farm balances. The main output 'sold milk' was calculated according to the monthly official milk-yield-performance control data less the amount of milk the calves needed for a minimum period of 3 months as stipulated by the organic agriculture regulations.

Results and Discussion

For all farms the farm-gate balance for N, P and K is 43, −2.8 and 0.8 kg ha^{-1}, respectively (Table 3). Though in both regions, some differences in structure and performance exist, the quantities of imported and exported nutrients as well as the balances are similar. In the Allgaeu region, the range for P is wider. Assuming so-called unavoidable volatile ammonia losses during manure and slurry storage and spreading of about 30 kg N LU^{-1},[16] the resulting average N surplus related to 1.35 LU ha^{-1} on average (Table 1) is very low. Mean P and K balances are close to zero, as reported in other investigations[7,17–21], indicating that there is likely to be little adverse environmental impairment (e.g. eutrophication).

The calculated product-related N balance of 8.2 g kg^{-1} milk (Table 4) is low compared to dairy farms in northern Germany (Scheringer[22], p. 28: organic and conventional, 16 and 24 g kg^{-1} milk, respectively) and in Denmark (Dalgaard et al.[4]: organic and conventional, 22 and 29 g kg^{-1} milk, respectively). The variations of the K balances are extremely high and those for the N balances comparably low.

Nutrient use efficiency for all farms on average calculated as the proportion of input to output is area-related high for N (45%), P (164%) and K (91%). Scheringer[22] (p. 28) calculated lower N-efficiency rates of 27 and 25% for organic and conventional dairy farms, respectively. van der Werff et al.[23] report a higher N efficiency of 31% for organic compared to 12% for conventional dairy farms in The Netherlands, as do Halberg et al.[24] for Danish dairy farms (25% organic, 16% conventional).

Table 4. Annual product-related balance of farm-gate nutrient budget (g kg^{-1} milk) [mean, coefficient of variation (%) in parentheses, range underneath].

	N	P	K
All farms	8.2 (52)	−0.5 (132)	0.1 (1015)
$n = 26$	2.1–17.1	−2.8 to 0.9	−2.4 to 3.9
NRW	9.5 (42)	−0.5 (101)	−0.2 (643)
$n = 12$	2.1–15.8	−1.5 to 0.2	−2.4 to 2.3
Allgaeu	7.0 (62)	−0.6 (155)	0.5 (342)
$n = 14$	2.5–17.1	−2.8 to 0.9	−1.3 to 3.9

N-flow components

As expected, a high proportion (72%) of the N input is caused by symbiotic N_2 fixation of the legumes (Table 5). The average N input via purchased feed of all farms is considerably lower (25%), but can reach 58% in both regions. In the Allgaeu region, the share of legumes of the total input is higher than for the farms in NRW, while feed-N input is lower. The quantities of purchased feed on the Allgaeu farms are lower, as is the milk yield per cow (Table 1), whereas grassland yields are higher. In general, the nutrient input via purchased straw and livestock is very small particularly for N and P. Nitrogen output is dominated by the milk sold to the dairy (Table 5), but this component can be down to 38% if higher quantities of cash crops are sold. However, on average, cash crops account for only 11% in NRW and 3% in the Allgaeu region. Compared to cash crops, the mean N output via sold animals is higher (mainly bull calves and cull cows).

P-flow components

Average P balances are slightly negative (Table 3), whereas in conventional farming very much higher surpluses are reported (up to 32 kg P ha^{-1}), which are still slightly positive even if optimized in experiments to the highest extent possible[25,26].

Table 5. Nitrogen farm-gate budget: share (%) of input and output components [rounded mean, coefficient of variation (%) in parentheses, range underneath].

	Input			Output		
	N_2 fixation	Feed	Straw, animals, seed potatoes	Milk	Cash crops	Animals
All farms	72 (23)	25 (68)	3 (203)	79 (15)	7 (192)	14 (31)
$n = 26$	34–100	0–58	0–26	38–92	0–55	7–24
NRW	66 (24)	32 (44)	2 (149)	74 (19)	11 (149)	15 (32)
$n = 12$	34–88	12–58	0–7	38–88	0–55	7–24
Allgaeu	77 (21)	19 (93)	4 (202)	84 (10)	3 (254)	13 (30)
$n = 14$	42–100	0–58	0–26	63–92	0–28	8–21

Table 6. Phosphorus farm-gate budget: share (%) of input and output components [rounded mean, coefficient of variation (%) in parentheses, range underneath].

	Input			Output		
	Feed	Straw	Animals/seed potatoes	Milk	Cash crops	Animals
All farms	86 (29)	11 (224)	2 (174)	75 (19)	8 (206)	17 (32)
$n = 26$	2–100	0–98	0–15	29–90	0–65	6–30
NRW	94 (9)	3 (188)	3 (137)	71 (18)	11 (147)	18 (31)
$n = 12$	77–100	0–16	0–15	39–85	0–52	9–30
Allgaeu	79 (41)	19 (177)	2 (245)	78 (20)	6 (305)	17 (33)
$n = 14$	2–100	0–98	0–11	29–90	0–65	6–25

The P balances are determined by feed input and milk output (Table 6). The main P input is based on purchased feed reaching 100% of total P input in both regions. The main feed P input is lower in the Allgaeu region, because a high share of grassland often increases the need for straw, the share of which can be high, but the quantity low. P output beside milk is also through cash crops and sold animals. On some farms in both regions, the sale of cash crops and animals sums up to an output share of about 60–70%.

The highest P balance of 4 kg ha^{-1} (Table 3) was found for a farm that purchases roughage (hay and pellets), but does not grow cash crops. A pure permanent grassland farm in the Allgaeu region showed the lowest balance of −14 kg P ha^{-1}, because roughage is sold and almost no feed purchased. Soluble P content in the soil of that farm is very low, requiring mineral-P fertilization. Low soluble P- and K-soil content are often detected on farms with long-term organic management history[27–29]. After converting to organic agriculture, no fertilization is needed for many years if previous conventional farming caused nutrient-rich soils, which is still often the case in many European countries[30]. Additionally, the soil nutrient classification levels on which extension recommendations for fertilization are based, were lowered at least twice in the 1990s, and there are still uncertainties related to analyzing methods and interpretation schemes across Europe[31]. For this reason and because of a general abandonment of the use of processed fertilizers, organic farmers feel sometimes too comfortable with a no-fertilization management and do not realize that for some sites and soil substrates there is an increasing need for P and K.

K-flow components

Over all farms, the K balances are close to zero (Table 3). A deficit of 13 kg K ha^{-1} was found at one farm in NRW, which sells potatoes and sugar beet. The highest surplus of 15 kg K ha^{-1} at a pure permanent grassland farm in the Allgaeu region was due to the purchase of higher quantities of straw. Purchasing straw can contribute up to 96% of the K input (Table 7). However, on average, purchased feed generates 80% of the K input. Similar to P, most K is sold via milk, though cash crops can account for up to 62%.

Correlations

There is a close relationship between the amount of feed purchased and milk yield ($r = 0.53$, $P = 0.0057$) (see Haas et al.[9]), but no correlations between the farm-gate balances and milk yield or livestock density. However, farm-gate balances are positively related to the parameter 'purchased feed', in particular to the net quantity of purchased feed (Table 8), which is illustrated for N in Figure 1.

Table 9 shows that P and K balances are negatively correlated with output only. They are positive with input.

Table 7. Potassium farm-gate budget: share (%) of input and output components [rounded mean, coefficient of variation (%) in parentheses, range underneath].

	Input			Output		
	Feed	Straw Fertilizer[1]	Animals/seed potatoes	Milk	Cash crops	Animals
All farms	80 (38)	19 (160)	1 (213)	82 (26)	13 (166)	5 (89)
$n = 26$	4–100	0–96	0–12	36–98	0–62	2–23
NRW	85 (25)	13 (165)	3 (151)	73 (33)	22 (119)	5 (110)
$n = 12$	36–100	0–62	0–12	36–97	0–62	2–23
Allgaeu	75 (48)	24 (150)	0 (261)	90 (17)	6 (261)	4 (36)
$n = 14$	4–100	0–96	0–2	40–98	0–58	2–7

[1] Only one farm (in NRW) is using 11.7 kg ha^{-1} mineral K fertilizer, which is 62% of its total K input.

Table 8. Coefficient of correlation (r) (Pearson) between farm-gate balances and milk performance, parameters of purchased feed and output of milk and cash crops per year ($n = 26$ farms; n.s., not significant = $P > 0.11$).

	Farm-gate balance (kg ha^{-1})		
	N	P	K
Milk yield (kg cow^{-1})	$-0.04^{n.s.}$	$0.05^{n.s.}$	$-0.15^{n.s.}$
Purchased feed (t DM farm^{-1} yr^{-1})	$0.42^{P=0.032}$	$0.47^{P=0.014}$	$0.32^{P=0.104}$
Net purchased feed (feed purchased − cash crops sold) (t DM farm^{-1})	$0.55^{P=0.003}$	$0.66^{P<0.001}$	$0.58^{P=0.002}$
Share of purchased feed of total quantity of feed (DM basis)	$0.29^{n.s.}$	$0.55^{P=0.003}$	$0.34^{P=0.088}$
Share of feed of respective nutrient input	$0.14^{n.s.}$	$0.38^{P=0.059}$	$-0.10^{n.s.}$
Share of milk of respective nutrient output	$0.36^{P=0.073}$	$0.42^{P=0.031}$	$0.46^{P=0.019}$
Share of sold animals of respective nutrient output	$0.13^{n.s.}$	$0.60^{P=0.001}$	$0.10^{n.s.}$
Share of cash crops of respective nutrient output	$-0.38^{P=0.058}$	$-0.57^{P=0.002}$	$-0.46^{P=0.020}$

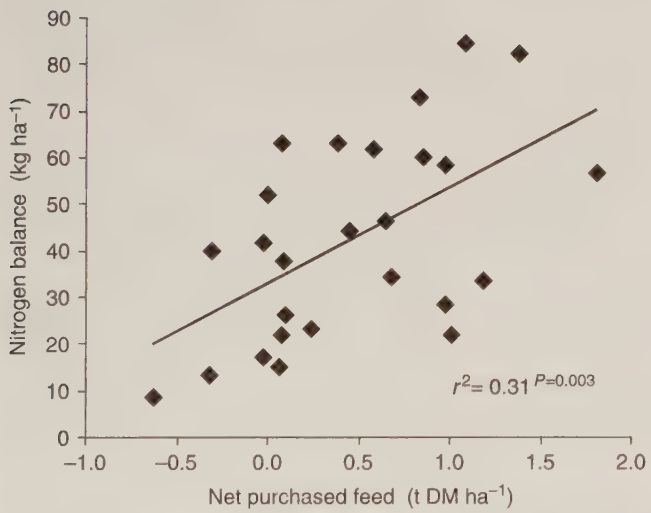


Figure 1. Relationship between net purchased feed and farm-gate nitrogen balance ($n = 26$ farms).

There are several reasons for the different N surpluses on the different farms: for example, the farms with the highest N surplus of 85, 82 and 73 kg N ha^{-1} beside N inputs of 115, 125 and 110 kg N ha^{-1} are characterized by livestock densities of 1.06, 1.3 and 1.35 LU ha^{-1}, large amounts of symbiotic N_2 fixation through a high proportion of grassland and legumes of 64–70% of the farm area and

Table 9. Coefficient of correlation (Pearson) between farm-gate balance and the amount of input and output for the respective nutrient ($n = 26$ farms; n.s., not significant = $P > 0.11$).

Farm-gate balance (kg ha^{-1})	Amount of input (kg ha^{-1})	Amount of output (kg ha^{-1})
N	$0.94^{P<0.001}$	$-0.03^{n.s.}$
P	$0.75^{P<0.001}$	$-0.58^{P=0.002}$
K	$0.88^{P<0.001}$	$-0.46^{P=0.018}$

annual milk yields of 7206, 6696 and 7916 kg cow^{-1}. Feeding strategy on these farms comprises 2.7, 0.7 and 1.0 t of concentrates per cow and year of which 46, 99 and 28%, respectively, are purchased. As hardly any cash crops are grown on these farms, the resulting sum of net purchased feed is 1.08, 1.38 and 0.83 t DM ha^{-1}, respectively.

In contrast, the two farms with the highest annual milk yields of 8788 and 8536 kg milk cow^{-1} show N surpluses of only 38 and 46 kg N ha^{-1}, respectively, which is close to the average of all farms. An intensive feeding strategy on these farms of annually 1.56 and 2.37 t DM concentrates and 0.56 and 0.43 t DM succulent feed (brewery grain, fruit residues) per cow with a considerable import of nutrients through purchased feed is complemented by cash crops, resulting in net amounts of purchased feed of 0.09 and 0.65 t DM ha^{-1},

Table 10. Coefficient of correlation (r) (Pearson) between N balance and parameters of legume cropping, mean, coefficient of variation (CV), minimum and maximum values ($n = 26$ farms; n.s., not significant = $P > 0.11$).

	r of N surplus (kg ha^{-1})	Mean	CV (%)	Minimum	Maximum
N surplus (kg ha^{-1})	1	42.6	51	8.4	84.6
Grassland area (ha)	$-0.33^{P=0.093}$	47.8	43	20.5	104.2
Share of grassland area to total farmed area (%)	$-0.47^{P=0.016}$	68.7	36	31.3	100.0
Grassland gross yield (t DM ha^{-1})	$0.04^{n.s.}$	8.84	23	44.0	116.0
Grass/red clover area (ha)	$0.53^{P=0.006}$	10.2	111	0	44.5
Share of grass/red clover area to total farmed area (%)	$0.79^{P<0.0001}$	11.1	85	0	27.1
Grass/red clover gross yield (t DM ha^{-1})[1]	$0.20^{n.s.}$	9.19	32	25.4	131.0
Sum of grassland and grass/red clover area (ha)	$-0.04^{n.s.}$	57.9	44	25.4	148.7
Share of grassland and grass/red clover area to total farmed area (%)	$-0.22^{n.s.}$	79.8	24	43.6	100.0
Share of N_2 fixation to N input	$-0.14^{n.s.}$	72.2	23	34.1	100.0

[1] Because five farms did not grow grass/red clover, $n = 21$ farms.

respectively. In addition to the fact that livestock density is lower than on the three aforementioned farms (0.78 and 0.97 LU ha^{-1}), as is the N-import through legumes, the share of permanent grassland and red clover is only 47 and 53% of the farm area, respectively.

These examples illustrate the impact livestock density (over all farms $r = 0.10^{n.s.}$) and the share of grassland and legumes of the farm area might have on a specific farm-gate N balance. However, these and all other parameters over all farms, except the net amount of purchased feed, are not correlated to the N surplus (Table 10, Fig. 1). There is a close positive relationship between the N surplus and the area of grass/red clover and between N surplus and proportion of grass/red clover (Table 10). However, because the share of grassland, which is much higher compared to that of grass/red clover, is negatively correlated and highly variable, the sum of grassland and grass/red clover and its share of the total farmed area are not correlated to the N surplus (Table 10).

Of the presented proportions of input components (Tables 5–7), only P via purchased feed (Table 8) and K via purchased animals and seed potatoes ($r = -0.41$, $P = 0.039$) are significantly related to the farm-gate balance of the respective nutrient. The proportions of output via sold milk and cash crops of the total output are more closely related to the nutrient balances (Table 8). An increasing share of cash crops of the nutrient output causes declining farm-gate balances, which can be explained by a comparable higher P content of cereals and higher K content of root crops, whereas an increasing proportion of milk to nutrient output relates to increasing nutrient balances. The impact of sold animals (comparable higher P content) on farm-gate balances is only significant and close for P (Table 8).

Comparison of systems

Nitrogen balances assessed by other researchers comparing organic and conventional dairy farms in Europe clearly result in low farm-gate surpluses on organic farms in Germany and Austria (Table 11). In countries with higher production intensities like Denmark, Sweden and The Netherlands, the surplus of organic dairy farms reaches 100 kg N ha^{-1}. However, according to the values in Table 11, the organic surplus is often half or a third of the surplus of conventional farms.

Thus, organic dairy farms can be considered as generally more environmentally sound regarding nutrient surplus and are more efficient in terms of nutrient surplus related to milk yield. The main reason for the difference between the systems is the use of mineral N fertilizers in conventional farming and, to a lower extent, the amount of purchased feed. If conventional farming is optimized by reducing use of mineral N fertilizers, as analyzed by Haas et al.[18] and Taube and Poetsch[32], or having similar stocking densities as shown by Kristensen[33], a N surplus close to that of organic farms can be obtained (Table 11).

These results match well with an organic dairy experiment by Weller and Bowling[45], which demonstrated that a self-sufficient system based solely on home-grown concentrates compared with a system based on purchased concentrates showed a superior environmental performance, as indicated, among other parameters, by lower nutrient surpluses. However, higher milk yields and the flexibility to overcome any imbalances and deficiencies (e.g. feed and feed quality) by purchasing feed were more attractive for the farmers, because an almost self-sufficient system demands higher management skills. Similar relationships and management demands are reported by Leach and Roberts[40] comparing clover- and fertilizer-based dairy systems.

Conclusions

Though different production structures and performance levels in organic dairy farming were investigated, the differences in nutrient balances were smaller than expected.

Table 11. Reported area-related farm-gate nitrogen balances of organic and conventional dairy farms in different parts of Germany and Europe (mean surplus[1], underneath mean annual performance per cow—which is not reported in some papers but has been added by personal email communication).

Reference, region/country and year of investigation if reported	Number of farms	Organic	Conventional optimized[2]	Conventional mainstream
The present study	26	43 kg ha^{-1}		
NRW and Allgaeu[3] 2001/02		6740 kg milk		
Haas et al.[18]	6 each	31 kg ha^{-1}	31 kg ha^{-1}	80 kg ha^{-1}
Bavarian Allgaeu[3] 1998		5280 kg milk	6390 kg milk	6760 kg milk
Scheringer[22] (p. 28)	7/10/[10 + 29]	56 kg ha^{-1}	77 kg ha^{-1}	146 kg ha^{-1}
Niedersachsen/Lower Saxony[3] 1998/99		5300 kg milk	6660 kg milk	6900 kg milk
Schumacher[34] (p. 121)	5 each	38 kg ha^{-1}		80 kg ha^{-1}
Hessen/Hesse[3] 1988/89		4100 kg milk		5100 kg milk
Taube et al.[35]	Typical mean in practice	80 kg ha^{-1}		169 kg ha^{-1}
Schleswig-Holstein[3] 1996		6000 kg milk		7500 kg milk
Gruber et al.[36]	Field-scale experiment	4.4 kg ha^{-1}		142 kg ha^{-1}
Austria		5870 kg milk		5880 kg milk
Taube and Poetsch[32]	40/51/66	24 kg ha^{-1}	25 kg ha^{-1}	37 kg ha^{-1}
Austria		4710 kg milk	4650 kg milk	6100 kg milk
Rosati and Aumaitre[37]	Not indicated	55 kg ha^{-1}		105 kg ha^{-1}
France (year not indicated)		6000 kg milk		8900 kg milk
Jonsson[38,46] [4]	Field-scale experiment	27 kg ha^{-1}		90 kg ha^{-1}
Sweden (northeast) 1990–2001		7892 kg milk		8038 kg milk
Cederberg and Flysjoe[39] (p. 19)	6/8[5]/9	71 kg ha^{-1}	114 kg ha^{-1}	158 kg ha^{-1}
Sweden (southwest) 2002		9400 kg milk	9130 kg milk	10,100 kg milk
Halberg et al.[24]	14/16	103 kg ha^{-1}		221 kg ha^{-1}
Denmark 1989–1991	Pilot farms	5600 kg milk		8200 kg milk
Kristensen[33]	133/93/212[6] on sandy soil	104 kg ha^{-1}	112 kg ha^{-1}	174 kg ha^{-1}
Denmark 2002		6958 kg milk	7764 kg milk	7764 kg milk
Leach and Roberts[40]	Field-scale experiment	90 kg ha^{-1}		258 kg ha^{-1}
Scotland (1989–)1996–1998		5717 kg milk[7]		8000 kg milk
Veer[41] and Pinxterhuis et al.[42]	Transition of research farm	101 kg ha^{-1}		253 kg ha^{-1}
The Netherlands:		6930 kg milk		8450 kg milk
1997 conventional – 2000 organic				
Smolders and Wagenaar[43]	11/91/91[8]	102 kg ha^{-1}	153 kg ha^{-1}	237 kg ha^{-1}
Beldman et al.[44]; The Netherlands[7]		7350 kg milk	8073 kg milk	7837 kg milk

[1] Method of farm-gate budget might vary, in particular because sometimes atmospheric N deposition is considered. Balances are corrected by excluding atmospheric N deposition if the values are listed.
[2] 'Optimized' conventional farms do not use mineral N fertilizers or are best performing or optimized in terms of N balance, or see table footnotes 5, 6 and 7 below.
[3] State or region of Germany.
[4] Data submitted via email dated 13 April 2005 by S. Jonsson, based on the report written in Swedish, project described by Bengtsson[17].
[5] Differentiation between conventional systems only by milk yield per ha, which is less than 7500 kg ha^{-1} for the farms 'conventional medium' and more than 7500 kg ha^{-1} for 'conventional high' listed here as 'optimized' and 'mainstream', respectively.
[6] Differentiation by system and mean lifestock density: organic 1.2 LU ha^{-1}, 'conventional optimized' 1.0 LU ha^{-1} and 'conventional mainstream' 1.7 LU ha^{-1}, which cover 8, 17 and 47% of the Danish milk production, respectively. Definition of livestock unit (LU) based on N excretion, e.g. 1 dairy cow of 8500 kg milk annually is 0.85 LU.
[7] It was not a truly organic system, but it was a grass–white clover-based system with minimized purchased concentrates, home-grown feed and no use of mineral N fertilizer.
[8] Data for the 11 organic farms by Smolders and Wagenaar[43] for the period 1998–2000. Data for the 91 conventional mainstream farms in year 1997; farms were continuously optimized predominantly by lowering the amount of mineral N fertilizer; in 2002, N surplus of these farms are reported as optimized by Beldman et al.[44].

Average farm-gate nutrient budgets for P and K are more or less balanced, but single farms show higher deficits or surpluses, which need to be evaluated in single-farm weak-point analyses. Farm-gate surpluses for P and K do not indicate an environmental burden. Higher deficits for P and K can, however, be important, particularly for farms with a higher proportion of nutrient output via cash crops, in view of productivity and crop quality.

Nitrogen surplus averages only 43 kg ha^{-1} and does not indicate a substantial environmental impact. However, surpluses on single farms reach 85 kg ha^{-1}. A clear relationship exists between the amount of feed purchased and the investigated farm-gate balances. Substantial purchases of concentrates can lead to higher N surpluses, but these are, in some cases, compensated by cash crops. On the other hand, higher N surpluses can also occur on farms with only moderate amounts of purchased feed, if livestock density and/or symbiotic N_2 fixation due to a high proportion of legume-based forage area are high; however, over all farms no correlation is detected between these parameters and N surpluses.

Although a general marked difference in farm gate N-surplus between organic and conventional dairy farming exists, there might only be a small difference between optimized conventional and intensified organic systems. Intensification in organic dairy farming must be assessed and considered carefully to further determine its environmental performance and profile.

Acknowledgments. Financial support by the Federal Ministry of Consumer Protection, Food and Agriculture is gratefully acknowledged. The authors express their sincere appreciation for the excellent cooperation of the organic dairy extension agents Christoph Drerup, Christian Wucherpfennig, Edmund Leisen, Jürgen Schlüter and Matthias Becker and the 26 farmers involved.

References

1 Rahmann, G., Nieberg, H., Drengemann, S., Fenneker, A., March, S., and Zurek, C. 2004. Bundesweite Erhebung und Analyse ökologisch wirtschaftender Betriebe. FAL Agricultural Research, Landbauforschung Völkenrode SH 276, Braunschweig, Germany. p. 26.

2 IFOAM (International Federation of Organic Agriculture Movements). 2002. Norms for Organic Production and Processing—IFOAM Basic Standards. IFOAM, Head Office, Bonn, Germany. p. 27.

3 van Beek, C.L., Brouwer, L., and Oenema, O. 2003. The use of farmgate balances and soil surface balances as estimator for nitrogen leaching to surface water. Nutrient Cycling in Agroecosystems 67:233–244.

4 Dalgaard, T., Halberg, N., and Kristensen, I.S. 1998. Can organic farming help to reduce N-losses?—experiences from Denmark. Nutrient Cycling in Agroecosystems 52:277–287.

5 Haas, G., Wetterich, F., and Geier, G. 2000. Life cycle assessment framework in agriculture on the farm level. Journal of Life Cycle Assessment 5:345–348.

6 Halberg, N., Verschuur, G., and Goodlass, G. 2005. Farm level environmental indicators: are they useful? An overview of green accounting systems for European farms. Agriculture, Ecosystems and Environment 105:195–212.

7 Haas, G. 1995. Betriebsbedingte Nährstoffbilanzen am Beispiel des Organischen Landbaus. In Verband der Landwirtschaftskammern und Bundesarbeitskreis Düngung (eds). Nährstoffbilanz im Blickfeld von Landwirtschaft und Umwelt. Frankfurt, Germany. p. 93–110.

8 Haas, G. and Deittert, C. 2004. Environmental impact assessment, nutrient matter flow analyses, and production efficiency of organic dairy farms at different intensity levels (Abstract in English). Research Report 514-43.10/02OE462, Bundesanstalt für Landwirtschaft und Ernährung, Bonn, Germany.

9 Haas, G., Deittert, C., and Köpke, U. 2007. Impact of feeding pattern and feed purchase on area- and cow-related dairy performance of organic farms. Livestock Science 106:132–144.

10 Boller, B.C. and Noesberger, J. 1987. Symbiotically fixed nitrogen from field-grown white and red clover mixed with ryegrasses at low levels of ^{15}N-fertilization. Plant and Soil 104:219–226.

11 Boller, B.C., Luescher, A., and Zanetti, S. 2003. Schätzung der biologischen Stickstoff-Fixierung in Klee-Gras-Beständen. Schriftenreihe Nr. 45 der Eidgenössischen Forschungsanstalt für Agrarökologie und Landbau, Zürich-Reckenholz, Switzerland. p. 47–54.

12 Weissbach, F. 1995. Über die Schätzung des Beitrags der symbiotischen N_2-Fixierung durch Weissklee zur Stickstoffbilanz von Grünlandflächen. Landbauforschung Völkenrode 45:67–74.

13 Haas, G. 2004. Nitrogen supply of vegetable and maize crops following winter green manure legumes (Abstract in English). Verlag Dr. Köster, Berlin, Germany.

14 Köpke, U. 1987. Symbiotische Stickstoff-Fixierung und Vorfruchtwirkung von Ackerbohnen (*Vicia faba* L.). Habilitationsschrift, University of Goettingen, Neuauflage 1996. Verlag Dr. Köster, Berlin, Germany.

15 Köpke, U. 1995. Nutrient management in organic farming systems: the case of nitrogen. Biological Agriculture and Horticulture 11:15–29.

16 Federal Ministry of Nutrition, Agriculture and Forestry. 1996. Anhang zur Musterverwaltungsvorschrift zur Düngeverordnung. Federal Ministry of Nutrition, Agriculture and Forestry, Bonn, Germany.

17 Bengtsson, H. 2005. Nutrient and trace element flows and balances at the Öjebyn dairy farm. PhD thesis no. 2005:2, Swedish University of Agricultural Sciences, Uppsala.

18 Haas, G., Wetterich, F., and Köpke, U. 2001. Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. Agriculture, Ecosystems and Environment 83:43–53.

19 Watson, C.A., Bengtsson, H., Ebbesvik, M., Loes, A.K., Myrbeck, A., Salomon, E., Schroder, J., and Stockdale, E.A. 2002. A review of farm-scale nutrient budgets for organic farms as a tool for management of soil fertility. Soil Use and Management 18:264–273.

20 Wieser, I., Hess, J., and Lindenthal, T. 1996. Nutrient balances on organically managed grassland farms in Upper Austria (Abstract in English). Bodenkultur 47:81–88.

21 Steinshamn, H., Thuen, E., Azzaroli Bleken, M., Tutein Brenoe, U., Ekerholt, G., and Yri, C. 2004. Utilization of nitrogen (N) and phosphorus (P) in an organic dairy farming system in Norway. Agriculture, Ecosystems and Environment 104:509–522.

22 Scheringer, J. 2002. Nitrogen on dairy farms: balances and efficiency. PhD thesis, University of Goettingen. Excelsior Publisher, Hohengandern, Germany.

23 van der Werff, P.A., Baars, A., and Oomen, G.J.M. 1995. Nutrient balances and measurement of nitrogen losses on

mixed ecological farms on sand soils in the Netherlands. Biological Agriculture and Horticulture 11:41–50.
24 Halberg, N., Steen Kristensen, E., and Sillebak Kristensen, I. 1995. Nitrogen turnover on organic and conventional mixed farms. Journal of Agriculture, Environment and Ethics 8: 30–51.
25 Aarts, H.F.M., Habekotté, B., and van Keulen, H. 2000. Phosphorus (P) management in the 'De Marke' dairy farming system. Nutrient Cycling in Agroecosystems 56:219–229.
26 Withers, P.J.A., Peel, S., Mansbridge, R.M., Chalmers, A.C., and Lane, S.J. 1999. Transfer of phosphorus within three dairy farming systems receiving varying inputs in feed and fertilizers. Nutrient Cycling in Agroecosystems 55: 63–75.
27 Gosling, P. and Shepherd, M. 2005. Long-term changes in soil fertility in organic arable farming systems in England, with particular reference to phosphorus and potassium. Agriculture, Ecosystems and Environment 105:425–432.
28 Loes, A.-K. and Ogaard, A.F. 2001. Long-term changes in extractable soil phosphorus (P) in organic dairy farming systems. Plant and Soil 237:321–332.
29 Nolte, C. and Werner, W. 1994. Investigation on the nutrient cycle and its components of a biodynamically-managed farm. Biological Agriculture and Horticulture 10: 235–254.
30 Tunney, H., Csatho, P., and Ehlert, P. 2003. Approaches to calculating P balance at the field-scale in Europe. Journal of Plant Nutrients and Soil Science 166:438–446.
31 Neyroud, J.-A. and Lischer, P. 2003. Do different methods used to estimate soil phosphorus availability across Europe give comparable results? Journal of Plant Nutrients and Soil Science 166:422–431.
32 Taube, F. and Poetsch, E.M. 2001. On-farm nutrient balance assessment to improve nutrient management on organic dairy farms. In J. Isselstein and G.H. Spatz (eds). Organic Grassland Farming. Symposium European Grassland Federation (EGF), 10–12 July 2001, Witzenhausen, Proceedings, Grassland Science in Europe, Vol. 6. British Grassland Society, Glos., UK. p. 225–234.
33 Kristensen, S. 2004. Nitrogen balance from dairy farms (2002). Danish Institute of Agricultural Science. Available at Web site: www.lcafood.org/processes/agriculture/N_balance_dairyfarms.htm (verified 12 April 2005).
34 Schumacher, U. 1996. Vergleichende nutztierökologische Untersuchungen auf ökologischen und konventionellen Milchviehbetrieben in Mittelhessen. PhD thesis, University of Giessen, Germany.
35 Taube, F., Wachendorf, M., Greef, M., and Wulfes, R. 1997. Perspectives of semi-intensive production systems for dairy farms in northern Germany (Abstract in English). Berichte über Landwirtschaft 75:586–603.
36 Gruber, L., Steinwender, R., Guggenberger, T., and Plakolm, G. 2001. Comparison of organic and conventional farming on a grassland farm—3rd communication: nutrient balances on supply/withdrawal basis and import/export basis (Abstract in English). Bodenkultur 52:183–195.
37 Rosati, A. and Aumaitre, A. 2004. Organic dairy farming in Europe. Livestock Production Science 90:41–51.
38 Jonsson, S. 2004. Öjebynprojektet-ekologisk production av livsmedel. Slutrapport. Röbäcksdalen Meddelar 5:2004. Department of Agricultural Research for Northern Sweden, Swedish University of Agricultural Sciences, Öjebyn.
39 Cederberg, C. and Flysjoe, A. 2004. Life cycle inventory of 23 dairy farms in south-western Sweden. Research Report, Swedish Institute for Food and Biotechnology. Available at Web site: www.sik.se/archive/pdf-filer-katalog/SR728(1).pdf (verified 24 March 2005).
40 Leach, K.A. and Roberts, J. 2002. Assessment and improvement of the efficiency of nitrogen use in clover based and fertilizer based dairy systems. 1. Benchmarking using farm gate balances. Biological Agriculture and Horticulture 20:143–155.
41 ter Veer, D. 2003. Mineralenoverschot Aver Heino drastisch gedaald na omschakeling. PraktijkKompas Rundvee 5:11.
42 Pinxterhuis, I., Hutschemaekers, B., and de Haan, M. 2003. Kosten en saldo Aver Heino hoger na omschakeling. PraktijkKompas Rundvee 5:10–11.
43 Smolders, G. and Wagenaar, J.P. (eds). 2004. Bioveem in beeld. Prakijk en onderzoek op 10 biologische melkveebedrijven, 1997–2001. Praktijkonderzoek Animal Sciences Group van Wageningen UR, Lelystad, The Netherlands.
44 Beldman, A.C.G., Doornewaard, G.J., Tomson, N.C., and Daatselaar, C.H.G. 2003. Strategie en cijfers: strategische plannen getoetst aan de werkelijkheid—trends en cijfers 1997–2002. Landbouw Econmisch Instituut. Available at Web site: www.praktijkcijfers.nl.
45 Weller, R.F. and Bowling, P.J. 2004. The performance and nutrient use efficiency of two contrasting systems of organic milk production. Biological Agriculture and Horticulture 22:261–270.
46 Fagerberg, B., Salomon, E., and Jonsson, S. 1996. Comparison between conventional and ecological farming systems at Öjebyn. Swedish Journal of Agricultural Research 26: 169–180.

Renewable Agriculture and Food Systems: 22(3); 233–238 doi:10.1017/S1742170507001792

Yield and fruit quality response of sweet pepper to organic and mineral fertilization

F.M. del Amor*

Instituto Murciano de Investigación y Desarrollo Agrario y Alimentario (IMIDA), c/ Mayor s/n, 30150 La Alberca, Murcia, Spain.
*Corresponding author: franciscom.delamor@carm.es

Accepted 19 November 2006 **Research Paper**

Abstract

Sweet pepper plants were grown in a greenhouse under three different cultivation methods (organic, integrated and conventional farming). During the crop cycle, plant growth and especially yield and fruit quality parameters were monitored to determine the effects of the different fertilization strategies. Plant fresh weight and total leaf fresh weight were progressively reduced, relative to the other treatments, in the organic treatment compared with the conventional, and at the end of the crop cycle these parameters were reduced by 32.6 and 35% respectively. This reduction in growth was directly correlated with plant nitrate concentration and, at the end of the study, nitrate concentration was reduced almost completely in the organic treatment. Despite the important effect on growth, no significant differences in total marketable yield were observed between conventional and organic farming, although integrated farming showed the highest yield in the extra and first class fruit categories. Organic farming increased antioxidant activity but reduced both chlorophylls and β-carotene. Fruit firmness, pericarp thickness, pH and total soluble solids content showed higher values with the organic method, but these differences were not significant with respect to the conventional method. Our results show the advantages of the organic fertilization, from both environmental and economic perspectives, if proper dosage is added to the crop and the demonstrated buffer capacity of these plants, with respect to maintaining yield under nutrient depletion at later stages of development, is taken into account.

Key words: *Capsicum annuum* L., nitrate, N limitation, antioxidant activity, fertilization strategies

Introduction

Agriculture, in the past dominated mainly by productivity, now also has to consider other objectives like the quality of crop products, the low cost of production and the environmental impact of crops and cropping systems, and hence increased nitrogen (N) use efficiency[1]. Improved nitrogen management has become essential in recent years because of increased levels of nitrate in groundwater associated with high rates of N applied to crops. The application rates, timing, and methods of both N fertilization and irrigation are ways to improve N management[2]. During the past 50 years, global N fertilizer applications have increased steadily, rising almost 20-fold to the present rate[3] of 10^{11} kg yr^{-1}. Horticultural crop species such as sweet pepper are traditionally supplied with high levels of chemical fertilizers, contributing to increased contamination in aquifers, rivers or lakes. In vegetable crops, the yield response to nitrogen can be dramatic, and the cost of the fertilizer often small compared with the cost of lost yield. Therefore, farmers usually over-fertilize with nitrogen, rather than risk under-fertilizing and suffering lost revenue[4].

Organic fertilization could be a useful tool to minimize soil contamination while improving fruit quality. However, it is often difficult to identify and measure the easily mineralizable fraction, which arises from the effects of temperature and moisture supply on N-cycle processes[5]. Organic farming has therefore to develop protocols to determine the minimum rates for different types of organic fertilizer in order to optimize plant growth and fruit quality compared with other agricultural production methods. Differences in the management of soil fertility affect soil dynamics and plant metabolism, which result in differences in plant composition and nutritional quality[6]. Many studies have pointed out the effect of soil management on fruit quality. Recently, Benbrook[7] reported that organic farming elevated antioxidant levels in about 85% of the cases studied to date and, on average, levels are about 30% higher compared to food grown conventionally. However, many studies have pointed out significant variation in the results,

© 2007 Cambridge University Press

both within and among studies, due to maturity at harvest, temperature or surface bruises[8]. Our study has been developed to control for theses issues, by using the same greenhouse, in separate individual lysimeters, controlled climate conditions, and minimizing external factors that might affect the treatments. The aim of this work was to characterize and to evaluate, under the same climate conditions, the yield and fruit quality of sweet pepper under organic fertilization management, compared to integrated and conventional systems in which chemical fertilizer was added at different dosages through the crop cycle to avoid nutrient depletion.

Materials and Methods

Plant material and growth conditions

Sweet pepper plants (*Capsicum annuum* L.) cv. Requena, California type, were transplanted from a commercial nursery on 18 December 2003. Plants were grown in a plastic greenhouse which was divided into eight independent lysimeters. The use of lysimeters avoids any interference or contamination from each irrigation water or drainage. Each lysimeter was 7.6 m long and 6.5 m wide, with seven lines of drip irrigation and its own fertilizer and water control unit. The lysimeter contained a total of 126 plants with a $4\,l\,h^{-1}$-dripper per plant. The irrigation schedule was applied according to the US Weather Bureau Class A evaporation pan which was placed inside the greenhouse. Total water applied per lysimeter was $29 \pm 0.6\,m^3$. Each lysimeter received, before transplanting, $4\,kg\,m^{-2}$ of horse manure with the following characteristics, on a dry weight basis: organic material: 44.3%; C/N: 19.8; P_2O_5: 1.4%; total N: 1.3%; K_2O: 1.9%. This dosage was the common amount used in greenhouses to improve soil characteristics and allows bio-fumigation at the end of the crop cycle, whatever crop method was applied. The conventional treatment consisted of the application of the local farmers' fertilizer dosage ($g\,m^{-2}$) N: 30.7; P_2O_5: 28.3; MgO: 10.5; K_2O: 54.7; CaO: 27.5, to each lysimeter throughout the crop cycle. The integrated treatment received half of the fertilizer dosage of the conventional treatment. No chemical fertilizers were added to the organic treatment. The greenhouse had automated control of relative humidity, by a fog system.

Growth analysis and nitrate determination

Forty-eight plants were harvested at each sampling time: 5, 57, 104, 152 and 186 days after transplanting (DAT). Total plant stem and leaves were weighed. Dry weight was determined after a minimum of 72 h at 70°C. Nitrate concentration was calculated in the dry matter of leaves, stem and roots (only the upper part). Nitrate was extracted from 0.5 g of ground material using 25 ml of deionized water, with centrifugation for 30 min. Five milliliters of extract were mixed with 5 ml of 2 *M* $(NH_4)_2SO_4$, to adjust ionic strength, before nitrate determination with a Thermo-ORION 950 ion selective electrode.

Fruit analyses

Marketable fruit quality was determined from the three central rows of plants in each lysimeter, avoiding two edge rows due to the environmental 'edge' effect. Fruit harvesting was performed at the fully mature green stage of ripening. Marketable characteristics for California peppers were defined as: *Extra*: uniform color, good health state, square shape, and weight >190 g; *class I*: uniform color, good health state, non-square shape and weight >225 g; *class II*: uniform color, good health state, non-square shape and weight of 224–170 g; *class III*: uniform color, good health state, non-square shape and weight of 100–170 g; *non-marketable*: remaining fruits rotten, fruits with more than 20% of their surface having blossom-end rot (BER) or lighter than 100 g.

Forty-eight fruits were weighed, washed with deionized water and seeds removed. Antioxidant activity was determined in the liquefied and centrifuged fruit sample using ABTS [2,2′-azinobis(3-ethylbenzothiazoline-6-sulfonic acid)] according to the method proposed by Miller et al.[9]. The method is based on the ability of antioxidant molecules to quench the long-lived $ABTS^+$, a blue–green chromophore with characteristic absorption at 734 nm, compared with that of Trolox (6-hydroxy-2,5,7,8-tetramethychroman-2-carboxylic acid), a water-soluble vitamin E analog. The addition of antioxidants to the preformed radical cation reduces it to ABTS, the decolorization being determined. Carotene and chlorophylls were determined following the method of Nagata and Yamashita[10]: 1 g of fruit was homogenized with 15 ml of acetone/hexane (4 : 6) and the two fractions were separated by centrifugation at 5000 rpm for 7 min. The supernatant was collected for determination of pigment content in a spectrophotometer at 663, 645, 505 and 453 nm. β-Carotene was quantified according to the equation: β-Carotene (mg/100 ml) = $0.216A_{663} - 1.22A_{645} - 0.304A_{505} + 0.452A_{453}$; chlorophyll A (mg/100 ml) = $0.999A_{663} - 0.0989A_{645}$; chlorophyll B (mg/100 ml) = $-0.328A_{663} + 1.77A_{645}$. The fruit firmness was determined on fruit with intact skin by using a Bertuzzi FT011 penetrometer, fitted with an 8-mm-diameter probe. Total soluble solids (TSS) content was measured in an Atago N1 refractometer and expressed as °Brix.

Statistical analyses

The experimental design consisted of three treatments (conventional, integrated and organic farming). Conventional and integrated treatments had three blocks (lysimeters), while the organic treatment had two blocks (the greenhouse had eight lysimeters). Each block had 126 plants. Each conventional and integrated treatment consisted of 378 plants and 252 plants in the organic treatment. In order to obtain enough replicates, each complete row of plants was considered a replicate. Biomass variables were

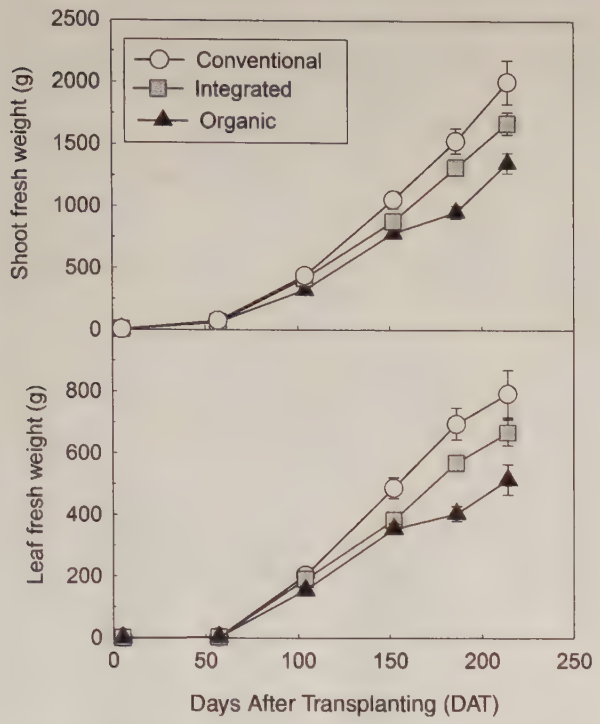


Figure 1. Comparison of the sensitivity of plant fresh weight and leaf fresh weight to the cultivation method. Vertical bars represent the standard error of the mean.

transformed to their logarithms before analysis and were judged to be normally distributed and homoscedastic by the Kolmogorov–Smirnov–Lilliefors and Levene tests. The SPSS v. 7.0 statistical package (SPSS Inc., Chicago, Illinois) was used to calculate significant differences by analysis of variance (ANOVA), and means were compared at probability $P < 0.05$.

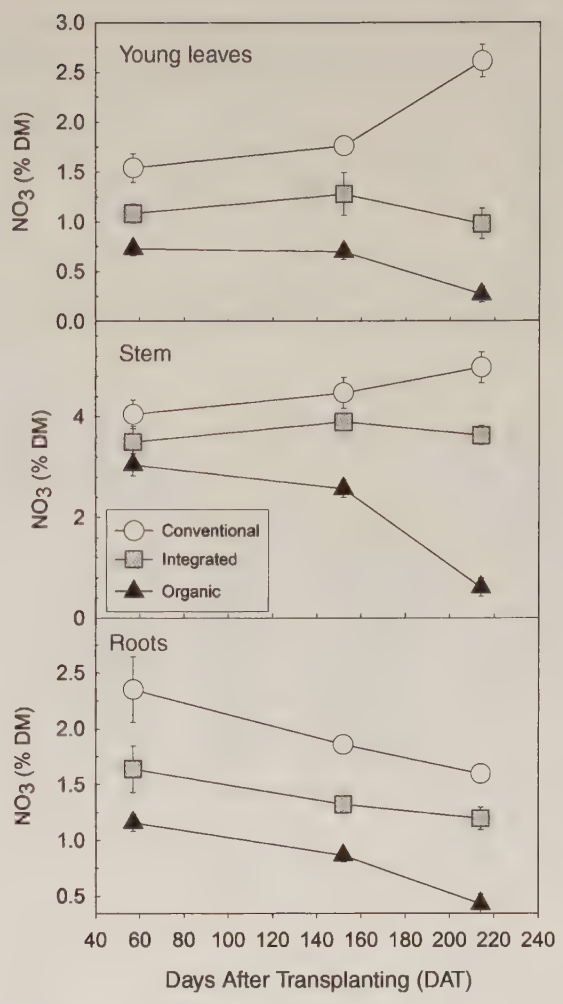


Figure 2. Effect of the fertilization method on nitrate concentration in leaves, stem and roots. Vertical bars represent the standard error of the mean.

Results and Discussion

As a result of only the initial pre-planting addition of manure, plant growth was not limited by nutrient availability in the soil during the first stages of growth in the organic treatment (Fig. 1). However, as plant biomass increased, the organic treatment reduced growth, and at the end of the crop cycle shoot fresh weight and total leaf fresh weight were reduced by 32.6 and 35%, respectively, compared to the conventional treatment. Organic N management requires knowledge of the response of crop growth processes to N. Therefore, depletion and/or shortage of N indicates that either the crop cannot maintain its leaf area expansion rate or cannot maintain its leaf and plant N concentration[11]. The effect on leaf expansion of canopies is brought about in a large part by N supply. The significant effect of N supply on leaf expansion and on branching appears a general response in many crops[1] and its effects on plant growth differ from those of K[12] or Ca[13]. In the organic plots, only a small percentage of the soil-derived N would be available at any given point in time because it must first be mineralized by microbes to a plant-available form such as NH_4^+ or NO_3^- and the amount mineralized may not be enough to meet crop N needs during later growth periods. On the other hand, limited N sources in the soil at a late stage of the crop cycle could be a key factor for reducing N losses[14] and reducing nitrate contamination. Our data showed the effect of different fertilization strategies on nitrate concentration in leaves, stems and roots (Fig. 2). In these organs, nitrate concentration was decreased in both the integrated and, especially, the organic treatment. At the end of this study (214 DAT) plant nitrate concentrations in the organic treatment were almost negligible; thus, nitrate concentration in the stems was reduced by 80.2% with respect to the initial concentration while nitrate concentrations in leaves and roots were reduced by 60 and 62% respectively. This agrees with experiments of Martinez et al.[15] and Starkey and Andersson[16]. Thus stems can act as storage organs for nitrogen and play an important role in adjustment to N limitation[17,18].

Despite the important effect on plant growth in the organic treatment, total marketable fruit yield was affected by the fertilization treatment only to a minor extent

Table 1. Effect of the fertilization method on total marketable fruit yield and fruit quality category of sweet pepper.

Treatment	Total marketable yield ($kg\,m^{-2}$)	Extra and class I ($kg\,m^{-2}$)	class II and III ($kg\,m^{-2}$)	Non-marketable ($kg\,m^{-2}$)
Conventional	7.34	1.96[a]	5.37	1.34
Integrated	7.99	2.45[b]	5.54	1.03
Organic	7.33	1.91[a]	5.42	1.40
ANOVA	ns	**	ns	ns

Within each column, different letters following the means indicate significant differences at $P \leqslant 0.05$.
ns, **, Non-significant differences or significant differences at $P \leqslant 0.01$ respectively.

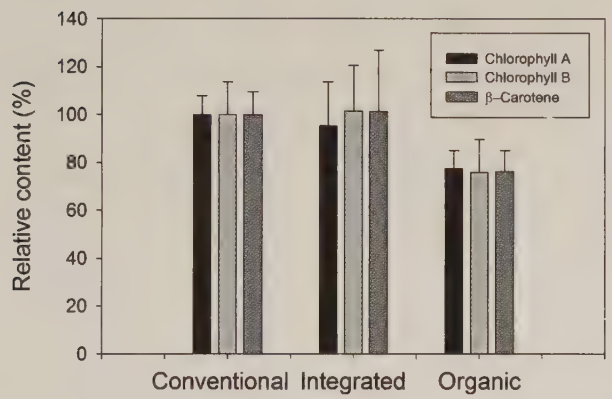


Figure 3. Relative contents of chlorophylls A and B and β-carotene in fruits from different cultivation methods. Vertical bars represent the standard error of the mean.

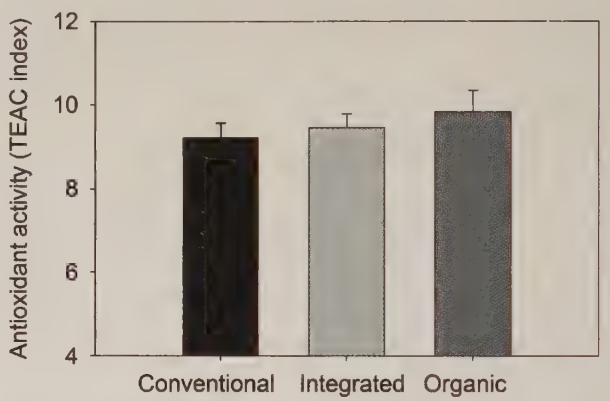


Figure 4. Antioxidant activity, expressed as the Trolox equivalent antioxidant capacity (TEAC) index of fruits, as affected by the cultivation method. Vertical bars represent the standard error of the mean.

(Table 1). The organic treatment did not show a significant difference ($P \leqslant 0.05$) with respect to the conventional treatment, even though no chemical fertilizer was added during the crop cycle. As has been pointed out previously, nitrate pools in the stems could act to regulate and maintain fruit yield at the expense of vegetative growth. On the other hand, higher nutrient availability in the conventional treatment (increased nitrate concentration in both leaves and stem) could contribute more to the vegetative components (leaves and stems) of the plant than the generative components (fruits). These results also agree with many studies showing that high rates of nitrogen induce vigorous vegetative growth to the detriment of fruit production[19]. Siddiqi et al.[20] also pointed out that reduction of macronutrient concentrations to 50 or 25% of the control levels had no adverse effect on fruit yield, highlighting the enormous buffer capacity of plants to store nitrogen. The lack of yield response to an additional fertilization is consistent with other studies which found that pepper requires low N fertilization rates for near-maximum production[21,22]. The integrated treatment (half the fertilizer dosage of the conventional treatment) showed the highest amounts of the extra and first-class fruit categories but no differences between treatments were observed for the second, third and the non-commercial fruits.

The organic treatment showed significantly ($P \leqslant 0.05$) lower levels of chlorophyll A and β-carotene compared with the conventional and integrated treatments (Fig. 3). Thus, chlorophylls A and B and β-carotene were reduced by 22.5, 24 and 23.8% respectively. As much as 75% of the total nitrogen in a plant is required for normal chloroplast formation[23]. Therefore, N content is often highly correlated with leaf chlorophyll concentration and the reductions in the organic treatment are likely related to the corresponding decrease in the soil N availability. The total antioxidant activity in organic fruits increased slightly (3.8%) compared with the conventional treatment (Fig. 4) and was similar to the values reported by Pellegrini et al.[24]. Plant antioxidants are vital constituents in foods, promoting both plant and human well-being. They promote human health by neutralizing cell damage caused by free radicals and dioxygen or peroxide molecules[7]. The consumption of fruits and vegetables has been inversely associated with morbidity and mortality from degenerative diseases[25]. Although it is not known which dietary constituents are responsible for this association, antioxidants appear to play a major role in the protective effect of plant foods[26]. The carotenoid pigments in fresh peppers have been widely studied, and shown to improve color retention during processing and storage[27]. Thus, the green color of the fruit is due principally to the presence of chlorophyll and the carotenoids typical of the chloroplast, as well to β-carotene[28]. It has been found that β-carotene is the predominant pigment for green peppers[29].

Table 2. Effect of the cultivation method on fruit dry matter content, fruit firmness and pericarp thickness and on the pH, electrical conductivity (EC) and TSS of fruit juice. ns, Non-significant differences at $P \leqslant 0.05$.

Treatment	Dry matter content (%)	Firmness (kg)	Pericarp thickness (mm)	pH	EC ($dS\,m^{-1}$)	TSS (°Brix)
Conventional	8.38	4.89	5.61	5.32	4.20	4.98
Integrated	8.08	4.47	5.70	5.30	4.37	4.84
Organic	8.26	5.08	6.12	5.33	3.87	5.02
ANOVA	ns	ns	ns	ns	ns	ns

Nitrogen levels in production systems have been negatively correlated with antioxidant content while yields typically are positively correlated. This relationship has been labelled the 'dilution effect'[30] and, according to this relationship, vitamin, mineral and antioxidant levels in food often decline as crop yields increase[7]. Our data show a small increase in the antioxidant capacity in the organic fruits; likely related to N depletion. That depletion in N could lead to a significant growth reduction and to a minor effect on the antioxidant capacity of the fruit; mainly due to a stress condition rather than the dilution effect, as fruit dry matter and total yield were not affected. Fruit firmness, pericarp thickness, pH and TSS showed higher values in the organic treatment but these differences were not significant ($P < 0.05$) with respect to the conventional treatment (Table 2).

Our data show that, with the proper manure dosage, chemical fertilizers could be reasonably avoided in sweet pepper cultivation, lowering production costs and reducing ground water pollution without decreasing fruit yield and with only a minor effect on fruit quality.

Acknowledgements. This research was supported by project RYC-2003-004806 from the Spanish Ministry of Science and Technology. We thank D.J. Walker for English revision of the manuscript, P. Marín, J. Navarro and C. Marín for valuable assistance with the measurements and J.M. Navarro for assistance in the antioxidant determination.

References

1 Gastal, F. and Lemaire, G. 2002. N uptake and distribution in crops: an agronomical and ecological perspective. Journal of Experimental Botany 53:789–799.
2 Li, M. and Yost, R.S. 2000. Management-oriented modeling: optimizing nitrogen management with artificial intelligence. Agricultural Systems 65:1–27.
3 Glass, A.D.M. 2003. Nitrogen use efficiency of crop plants: physiological constraints upon nitrogen absorption. Critical Reviews in Plant Sciences 22:453–470.
4 Tremblay, N., Scharpf, H.-C., Weier, U., Laurence, H., and Owen, J. 2001. Nitrogen Management in Field Vegetables. A Guide to Efficient Fertilisation. Agriculture and Agri-Food Canada. p. 65. Available at Web site: http://sci.agr.ca/stjean/publication/bulletin/nitrogen-azote_e.htm (verified 19 January 2007).
5 Mulvaney, R.L., Khan, S.A., Hoeft, R.G., and Brown, H.M. 2001. A soil organic nitrogen fraction that reduces the need for nitrogen fertilization. Soil Science Society of America Journal 65:1164–1172.
6 Worthington, V. 2001. Nutritional quality of organic versus conventional fruits, vegetables, and grains. Journal of Complementary and Alternative Medicine 7:161–173.
7 Benbrook, C.M. 2005. Elevating Antioxidant Levels in Food through Organic Farming and Food Processing. Available at Web site: http://www.organic-center.org/reportfiles/Antioxidant_SSR.pdf (verified 28 October 2004).
8 Bourn, D. and Prescott, J.A. 2002. Comparison of the nutritional value, sensory qualities and food safety of organically and conventionally produced foods. Critical Reviews in Food Science and Nutrition 42:1–34.
9 Miller, N.J., Sampson, J., Candeias, L.P., Bramley, P.M., and Rice-Evan, C.A. 1996. Antioxidant activities of carotenes and xanthophylls. FEBS Letters 384:240–242.
10 Nagata, M. and Yamashita, I. 1992. Simple method for simultaneous determination of chlorophyll and carotenoids in tomato fruit. Journal of the Japan Society for Food Science Technology 121:1117–1121.
11 Van Delden, A. 2001. Yield and growth components of potato and wheat under organic nitrogen management. Agronomy Journal 93:1370–1385.
12 Del Amor, F.M. and Marcelis, L.F.M. 2004. Regulation of K uptake, water uptake, and growth of tomato during K starvation and recovery. Scientia Horticulturae 100:83–101.
13 Del Amor, F.M. and Marcelis, L.F.M. 2003. Regulation of nutrient uptake, water uptake and growth under calcium starvation and recovery. Journal of the Horticultural Science and Biotechnology 78:343–349.
14 Dinnes, D.L., Karlen, D.L., Jaynes, D.B., Kaspar, T.C., Hatfield, J.L., Colvin, T.S., and Cambardella, C.A. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained midwestern soils. Agronomy Journal 94:153–171.
15 Martinez, V., Del Amor, F.M., and Marcelis, L.F.M. 2005. Growth and physiological response of tomato plants to different periods of nitrogen starvation and recovery. Journal of Horticultural Science and Biotechnology 80:147–153.
16 Starkey, K.R. and Andersson, N.E. 2000. Effects of light and nitrogen supply on the allocation of dry matter and calcium in poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch). Journal of Horticultural Science and Biotechnology 75:251–258.
17 Steingrover, E., Oosterhuis, R., and Wieringa, F. 1982. Effect of light treatment and nutrition on nitrate accumulation in Spinach (*Spinacia oleraceae* L.). Zeitschrift fur Planzenphysiologie 107:97–102.
18 De Groot, C.C., Marcelis, L.F.M., Van Den Boogaard, R., and Lambers, H. 2002. Interactive effects of nitrogen and

irradiance on growth and partitioning of dry mass and nitrogen in young tomato plants. Functional Plant Biology 29:1319–1328.

19 Papadopoulos, A.P. 1991. Growing Greenhouse Tomatoes in Soil and in Soilless Media. Agriculture and Canada Publication. Available at Web site: http://sci.agr.ca/harrow/publications/pub 1865_e.htm (verified 19 January 2007).

20 Siddiqi, M.Y., Kronzucker, H.J., Britto, D.T., and Glass, A.D.M. 1998. Growth of a tomato crop at reduced nutrient concentrations as a strategy to limit eutrophication. Journal of Plant Nutrition 21:1879–1895.

21 Carballo, S.J., Blankenship, S.M., and Sanders, D.C. 1994. Drip fertigation with nitrogen and potassium and postharvest susceptibility to bacterial soft rot of bell peppers. Journal of Plant Nutrition 17:1175–1191.

22 Qawasmi, M., Mohammad, M.J., Najim, H., and Qubursi, R. 1999. Response of bell pepper grown inside plastic houses to nitrogen fertigation. Communications in Soil Science and Plant Analysis 30:2499–2509.

23 Kutik, J., Lubomir, N., Demmers-Derks, H.H., and Lawlor, D.W. 1995. Chloroplast ultrastructure of sugar beet (*Beta vulgaris* L.) cultivated in normal and elevated CO_2 concentrations with two contrasted nitrogen supplies. Journal of Experimental Botany 46:1797–1802.

24 Pellegrini, N., Serafini, M., Colombi, B., Del Rio, D., Salvatore, S., Bianchi, M., and Brighenti, F. 2003. Total antioxidant capacity of plant foods, beverages and oils consumed in Italy assessed by three different *in vitro* assays. Journal of Nutrition 133:2812–2819.

25 Gey, K., Puska, F.P., Jordanand, P., and Moser, U.K. 1991. Total antioxidant capacity of plant foods. Inverse correlation between plasma vitamin E and mortality from ischemic heart disease in cross-cultural epidemiology. American Journal of Clinical Nutrition 53:326–334.

26 La Vecchia, C., Altieri, A., and Tavani, A. 2001. Vegetables, fruit, antioxidants and cancer: a review of Italian studies. European Journal of Nutrition 40:261–267.

27 Markus, F.H., Daood, G., Kapitany, J., and Biacs, P.A. 1999. Change in the carotenoid and antioxidant content of spice red pepper paprika as a function of ripening and some technological factors. Journal of Agricultural and Food Chemistry 47:100–107.

28 Hornero-Mendez, D., Guevara, R.G.-L.D., and Minguez-Mosquera, M.I. 2000. Carotenoid biosynthesis changes in five red pepper (*Capsicum annuum*) cultivars during ripening. Cultivar selection for breeding. Journal of Agricultural and Food Chemistry 48:3857–3864.

29 Marin, A., Ferreres, F., Tomas, F.A., and Gil, M.I. 2004. Characterization and quantitation of antioxidant constituents of sweet pepper (*Capsicum annuum* L.). Journal of Agricultural and Food Chemistry 52:3861–3869.

30 Davis, D.R. and Riordan, H.D. 2004. Changes in USDA food composition data for 43 garden crops, 1950 to 1999. Journal of the American College of Nutrition 26:1–2.

Renewable Agriculture and Food Systems: 22(3); 239–240

Book Review

Farming for Us All: Practical Agriculture and the Cultivation of Sustainability. By Michael Mayerfeld Bell, Susan Jarnagin, Gregory Peter, and Donna Bauer. 2004. Pennsylvania State University Press, University Park, PA, USA. 299 p. US$22.50, ISBN 0271023872, paperback.

Three decades before *Farming for Us All* was published, I was lucky to be a junior member of a Center for the Biology of Natural Systems research group led by William Lockeretz and Barry Commoner. The National Science Foundation was funding us to study the implications of higher petroleum prices and spot energy shortages for Corn Belt farming. The research included a multi-year comparison of organic farms and neighboring operations managed under more conventional regimes. We visited some of the same Iowa counties as Bell and his colleagues, and met some of the same farmers. Though the focus was primarily economic and agronomic, we garnered tantalizing glimpses into the (social) construction of an alternative agriculture. For these reasons and others, I read this book with considerable interest. I was not disappointed.

Last year I assigned *Farming for Us All* as reading for a senior undergraduate and graduate seminar on the sociology of agriculture. We learned about contemporary changes in Midwestern agriculture and about the development of an increasingly sophisticated and complex sustainable farming movement. The book also taught us much about conceptualizing a research problem, conducting field research, and presenting the findings with sensitivity to multiple audiences. Thanks to an engaging writing style, reader-friendly design, and intelligent use of photographs, we were entertained as well as informed. I have since recommended the book to other graduate students who are conducting field research. I plan to teach with it again and expect to keep learning as I assimilate more of the central arguments and detailed side-discussions. It is a book to read and reread.

While this volume generated a positive reception from students, it is also well suited for informed and motivated readers with an interest in farming and new agricultural movements. Though some may find the discussions of conceptual problems and research strategies a bit rarified or abstruse, such topics are covered for the most part in the *Intermezzo* segments that appear at the end of each of the main sections of the book. These segments can be skipped by those who find such digressions of limited interest, though chances are few readers will elect to do so. The scholarly foundations of this monograph are confirmed by the extensive notes on sources, terms, and related debates in the social sciences, and by the long list of references. In these departments it does not skimp, but nor does it overpower or distract the reader.

While satisfying to the academic, this book focuses on practitioners and on the practical ideas that they co-generate. This is accomplished thanks in no small part to the strong alliance that the author maintained with practitioners and activists Susan Jarnagin, Gregory Peter, and Donna Bauer. With Bell, they carried out a decade of participatory field research (1994–2003) with several dozen Practical Farmers of Iowa (PFI) households and similar numbers of their neighbors. They also had extensive discussions with their non-farm associates in universities and other organizations. PFI was founded in 1985 by farmers looking for a way to respond to community decline, forced exodus, and environmental degradation. They were convinced that it must be possible to farm in economically and environmentally sound ways on moderate-sized farms that support community life. They hoped to promote this by organizing and sharing new forms of on-farm research and they were soon able to form a small research alliance with Iowa State University. By the early 2000s there were several hundred member households, about half of them directly involved in farming.

The writing of the book was mostly done by Bell, a sociologist. He reflects systematically on his learning journeys in the fields and farmyards of the Midwest, and is occasionally self-critical about the limits of his own agronomic knowledge. Nevertheless, he demonstrates breadth and intellectual maturity when he incorporates insights from sociology, history, social psychology, gender studies, agronomy and institutional economics. He writes with authority and appears justifiably confident in his ability to learn from the field and to make sense of details in ways that help us to answer larger questions.

Following an extended and informative 'Overture', the main arguments are explored in three parts that make for natural breaks when the book is being used in a course. The initial section focuses on 'The Uncertain Landscape of Industrial Agriculture' and serves up revealing portraits of large and small farmers wrestling with the pressures and contradictions of the agricultural economy. It provides, for example, stellar passages on the workings of the 'market' for rental land and on the moral economy inhabited by renters and landlords; on the declining practice of neighboring; on time management in farming households; and on the aspects of farming most valued by women and men.

Parts II and III focus on 'The Culture of Cultivation' and 'The Sustainable Landscape of Practical Agriculture'. Bell investigates the 'cultivation of knowledge' and propagation

© 2007 Cambridge University Press

of the self in (economic) landscapes that can be demanding and unforgiving. He sees farmers—still a male-coded category—as having to negotiate positive identities in communities that included landlords, employees, family members, neighbors, creditors, competitors, and advisors (not necessarily mutually exclusive categories). Choices with respect to farming practices, investments, and diversification are strongly linked to self-concepts and to one's membership in 'communities of knowledge'. These are networks of knowledge generation, exchange, and validation that connect people to trustworthy and useful information (useful in that it is consistent with one's own philosophy of farming).

Bell views all farmers as being wrapped up in the phenomenology of farming. This involves taken for granted approaches and techniques that are invoked even when one has doubts. Deep involvement with the practice of farming is intertwined with identity. 'What you know is who you are'. Farmers continue to farm because it is an identity and because, as an all-consuming endeavor that involves working with/against nature and intense social interactions in the overlapping arenas of gender, class, status, and ethnicity, it provides a phenomenal 'phenomenological buzz'. If this identity is involuntarily surrendered, as when farmers are forced off the land by economic circumstances, they may be susceptible to the identities offered up by others, including far-right groups such as militias and 'Patriots'.

Bell sees the PFI as a leading instance of a wider movement to develop new ways of being a farmer and of farming. He argues that the sustainable agriculture movement involves more than an alternative set of farming methods and social relations. It also calls forth a different social practice of agriculture that can be summed up as a different way of relating to difference—viewing it more as an opportunity for learning than as a threat. Farmers involved in such groups, he argues, learn to take into account more perspectives, experiences, and interests, and to incorporate these into ways of practicing agriculture that involve more dialogue (and less monologue). According to Bell, and to many of these innovative farmers, this dialogue should ultimately include us all because we all have a vital stake in developing and supporting a practical, sustainable agriculture that cares for farmers, animals, and the land even as it produces quality foods in abundance.

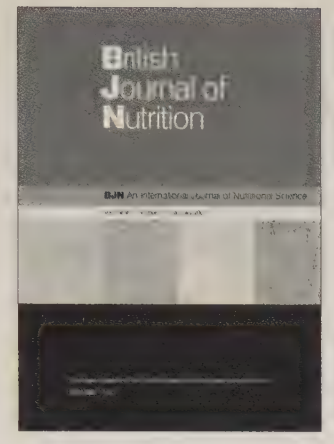
The terrain under investigation here is the interplay between dominant and widely promoted commercial–industrial approaches to farming, community, and nature, and alternative approaches such as those of the PFI. While PFI households share many characteristics and views with their non-affiliated neighbors, farmers who convert/switch to such new ways of farming often experience a kind of watershed transition—what Bell labels a phenomenological rupture. The new farm and the new self come together. The conditions and contradictions that contribute to such transformative changes include a varying mix of economic stresses, health and other environmental concerns, spiritual dissonance, doubts about the veracity of mainstream truth claims, and exposure to alternative development ideas in other venues. Such changes are also promoted by the sharing of on-farm research, group problem solving, other forms of networking and mutual support and (occasional) support from personnel in the co-operative sector, universities and government. Modest funding for sustainable agriculture from the U.S. Departments of Agriculture has likewise been influential.

While this volume incorporates many new insights and proposes some intriguing new conceptual tools, it is not always fully grounded in the sociology of agriculture literature on which it surely builds. It contains fewer references than one might expect to authors from that field who have studied the restructuring of the farm sector, farm households, farm work, the development of the organic sector, environmental conflicts and the sociology of agricultural resource management. Theoretical discussions are deliberately brief but sometimes over-simplify the intellectual debates that are revisited and reworked. There are tradeoffs when producing a book of manageable size for a wider readership.

Bell and his coworkers have investigated the social processes that block or promote changes in agrarian worldviews and identities, and in agricultural practices. The research opens interesting windows on the household- and community-level dynamics that underlie both adherence to convention and significant (non-conventional) innovation. We learn about rotational grazing, ridge tillage, hoop houses for hogs, and about conducting robust on-farm research using randomized, replicated, narrow-strip paired comparisons. We also learn much about the genesis of grassroots social change in North America and how to understand its complexity. Both the approach and the findings have broader relevance for researchers and social actors working in many sectors.

Dr Michael Gertler, Department of Sociology, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 5B8.
doi:10.1017/S1742170506001670

CAMBRIDGE JOURNALS



British Journal of Nutrition

Published on behalf of The Nutrition Society

British Journal of Nutrition
is available online at:
www.journals.cambridge.org/BJN

Editor-in-chief
P.C. Calder, University of Southampton, UK

To subscribe contact Customer Services

in Cambridge:
Phone +44 (0)1223 326070
Fax +44 (0)1223 325150
Email journals@cambridge.org

in New York:
Phone (845) 353 7500
Fax (845) 353 4141
Email
subscriptions_newyork@cambridge.org

British Journal of Nutrition is a leading international peer-reviewed journal covering research on human and clinical nutrition, animal nutrition and basic science as applied to nutrition. The Journal recognises the multidisciplinary nature of nutritional science and includes material from all of the specialities involved in nutrition research, including molecular and cell biology and the emerging area of nutritional genomics.

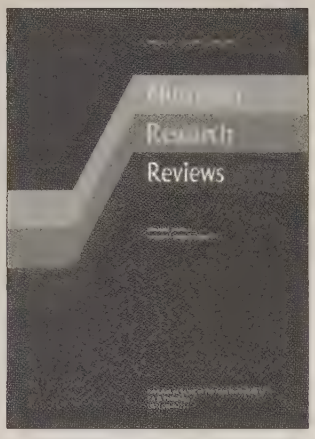
Price information is available at:
www.journals.cambridge.org/BJN

Free email alerts
Keep up-to-date with new material –
sign up at *www.journals.cambridge.org/register*

For a free online sample visit:
www.journals.cambridge.org/BJN

CAMBRIDGE UNIVERSITY PRESS

CAMBRIDGE JOURNALS



Nutrition Research Reviews

Published on behalf of The Nutrition Society

Nutrition Research Reviews
is available online at:
www.journals.cambridge.org/NRR

To subscribe contact Customer Services

in Cambridge:
Phone +44 (0)1223 326070
Fax +44 (0)1223 325150
Email journals@cambridge.org

in New York:
Phone (845) 353 7500
Fax (845) 353 4141
Email
subscriptions_newyork@cambridge.org

Editor-in-chief
D.A. Bender, University College London, UK

Nutrition Research Reviews presents up-to-date,concise, crtical reviews of key topics in nutritional science in order to advance new concepts and hypotheses. The Journal encourages the exchange of fundamental ideas on nutritional well-being in both humans and animals.

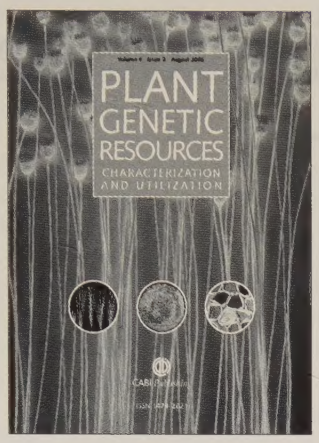
Price information is available at:
www.journals.cambridge.org/NRR

Free email alerts
Keep up-to-date with new material –
sign up at *www.journals.cambridge.org/register*

For a free online sample visit:
www.journals.cambridge.org/NRR

CAMBRIDGE UNIVERSITY PRESS

CAMBRIDGE JOURNALS



Plant Genetic Resources

Characterization and Utilization

Published on behalf of the National Institute of Agricultural Botany (NIAB)

Plant Genetic Resources
is available online at:
www.journals.cambridge.org/PGR

To subscribe contact Customer Services

in Cambridge:
Phone +44 (0)1223 326070
Fax +44 (0)1223 325150
Email journals@cambridge.org

in New York:
Phone (845) 353 7500
Fax (845) 353 4141
Email
subscriptions_newyork@cambridge.org

Editor-in-chief
Robert Koebner, Norwich, UK

Plant Genetic Resources is an international journal that brings together the many diverse topics concerned with plant genetic resources. Each issue gives you access to peer-reviewed research papers on genetic variation in plants, both crop and non-crop, as well as on the technical, socio-economic, legal and geo-political aspects of PGR. Many papers feature research directed to endangered non-crop and medicinal plants. The journal is of interest to researchers and scientists involved in the plant genetic resources community, including: breeders, all those with an interest in germplasm, policy makers, consultants and research students.

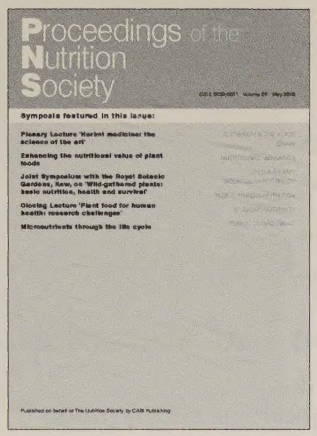
Price information is available at:
www.journals.cambridge.org/PGR

Free email alerts
Keep up-to-date with new material – sign up at *www.journals.cambridge.org/register*

For a free online sample visit:
www.journals.cambridge.org/PGR

CAMBRIDGE UNIVERSITY PRESS

CAMBRIDGE JOURNALS


Proceedings of the Nutrition Society
Symposia featured in this issue:
Plenary Lecture 'Korbel medicine: the science of the art'
Enhancing the nutritional value of plant foods
Joint Symposium with the Royal Botanic Gardens, Kew, on 'Wild-gathered plants: basic nutrition, health and survival'
Closing Lecture 'Plant food for human health: research challenges'
Micronutrients through the life cycle
Published on behalf of The Nutrition Society by CAB Publishing

Proceedings of the Nutrition Society

Published on behalf of The Nutrition Society

Proceedings of the Nutrition Society is available online at: www.journals.cambridge.org/PNS

Editor-in-Chief
C J Newbold, Institute of Rural Science, University of Wales Aberystwyth, UK

To subscribe contact Customer Services

in Cambridge:
Phone +44 (0)1223 326070
Fax +44 (0)1223 325150
Email journals@cambridge.org

in New York:
Phone (845) 353 7500
Fax (845) 353 4141
Email subscriptions_newyork@cambridge.org

Proceedings of the Nutrition Society publishes papers and abstracts presented by members and invited speakers at the scientific meetings of The Nutrition Society. The Journal provides an invaluable record of the scientific research currently being undertaken, contributing to 'the scientific study of nutrition and its application to the maintenance of human and animal health.'

Price information is available at:
www.journals.cambridge.org/PNS

Free email alerts
Keep up-to-date with new material – sign up at *www.journals.cambridge.org/register*

For a free online sample visit:
www.journals.cambridge.org/PNS

CAMBRIDGE UNIVERSITY PRESS

Notes for Authors

Renewable Agriculture and Food Systems publishes original research on biological, physical, or social science aspects of alternative and renewable agriculture and food systems. We particularly welcome multidisciplinary studies, but papers from a specific discipline are also invited. However, since *RAFS* readership is much broader than for a single-discipline journal, highly specialized terminology should be explained or avoided. The significance of a statement, or the reasoning behind a conclusion, may have to be spelled out more than in a more specialized journal. See www.journals.cambridge.org/jid_RAF for an explanation of the various categories of articles.

Units. Research papers should use the International (SI, or metric) system throughout. Occasional use of common unit equivalents in parentheses is permitted.

Title Page. The title page should give the following information (all flush left): 1) title of the paper; 2) names of the authors; 3) affiliation and office address of authors, e-mail of corresponding author, and 4) disclaimers, if any.

Abstract. The abstract should be 200 to 400 words, suitable for readers from a broad range of disciplines. It should avoid highly-specialized terminology that might be appropriate for a single-discipline journal. Take particular care that the significance of the work is made clear, even to readers from a different field.

Key Words. Provide subject matter key words suitable for use in scientific indexing.

References. References are based on the Vancouver system. They should be numbered consecutively in the order in which they first appear in the text using superscript Arabic numerals. Where a reference is cited more than once in the text, use the same number each time. In the reference list please give the names of all authors in the reference, never use "et al." Use full names of journals, institutions, conferences, etc. The reference list uses no quotation marks, italics, boldface or underlining. Only the names of books and periodicals are in initial capitals. Names of papers, book chapters, pamphlets, and bulletins are not capitalized.

Examples:

1. Leopold, A. 1991. The farmer as a conservationist. In S.L. Flader and J.B. Callicott (eds). The River of the Mother of God and Other Essays by Aldo Leopold. University of Wisconsin Press, Madison, WI. p. 255–265.
2. Brink, R.H. Jr, Dubach, P., and Lynch, D.I., 1960. Measurement of carbohydrates in soil hydrolyzates with anthrone. Soil Science 89:157–166.
3. Greenland, D.J., and Szabolcs, I., (eds). 1994. Soil Resilience and Sustainable Land Use. CAB International, Wallingford, UK.
4. Arshad, M.A., and Coen, G.M., 1992. Characterization of soil quality: Physical and chemical criteria. American Journal of Alternative Agriculture 7:25–31.
5. Coale, F.J. 1996. Descriptions of the soil test interpretive categories used by the University of Maryland Soil Testing Laboratory. SFM-3. University of Maryland, College Park.

Footnotes. *RAFS* does not use bibliographic or substantive footnotes. All bibliographic references should be at the end of the text. Instead of substantive footnotes, include the material in the main text or consider eliminating it.

Manuscript Preparation. The entire manuscript, including abstract and references, should be typed on one side of standard-size paper, double spaced, with margins of at least one inch all around. Starting with the title page, label all pages in the upper right-hand corner with the lead author's last name and the page number. Add line numbers to your manuscript, restarting numbering for each page. Do not use hyphens unless the hyphen is part of the word. Indicate on the title page who the corresponding author is, and supply a present postal address, fax number and email address. **The email address is particularly important** because page proofs will be sent electronically as a PDF file to the corresponding author for checking (see 'page proofs' section below for more detail). Tables should fit on one page, be numbered consecutively with Arabic numerals, and be on a separate sheet. Every figure and table should be mentioned at least once in the text. A detailed guide to formatting is available on the *RAFS* homepage at www.journals.cambridge.org/jid_RAF

Submission of Manuscripts. Please submit manuscripts via our manuscript submission and tracking site, **www.edmgr.com/rafs.**
Full instructions for electronic submission are available directly from this site and from www.journals.cambridge.org/jid_RAF. To facilitate rapid reviewing, communications for peer review will be electronic and authors will need to supply a current e-mail address when registering to use the system.

When submitting manuscripts authors will need to supply:

- Manuscript file.
- Covering letter, stating that the manuscript is an original contribution that has not been published elsewhere in substantially the same form, that it is not currently under consideration elsewhere, and that permission has been obtained for any copyrighted material used.

Copyright. Papers are accepted on the understanding that the work has been submitted exclusively to the Journal. Authors will be supplied with a transfer of copyright form with their proofs, this must be completed and returned to the publisher. Papers will not be published until the signed copyright disclaimer has been received.

Page Proofs. Once typeset, the corresponding author will receive page proofs by email as a PDF file. You will be asked to print the PDF proof and mark any corrections to the printout before mailing back to the proofreader. Alternatively, if you have no corrections or very few they can be returned to the proofreader by email. Full instructions will be sent with the page proofs.

Offprints. Authors are sent a PDF file of the final version of the article. Authors will be e-mailed an offprint order form along with the PDF proof.

A Final Note
Articles will be considered for publication in the *RAFS* only when submitted formally, in their final form, and formatted to the style of *RAFS*.

REVIEW

Renewable Agriculture and Food Systems

Volume 22 Number 3 September 2007

Research Papers

Does growing Canadian Western Hard Red Spring wheat under organic management alter its breadmaking quality?
H. Mason, A. Navabi, B. Frick, J. O'Donovan, D. Niziol and D. Spaner 157

Crop and cattle responses to tillage systems for integrated crop–livestock production in the Southern Piedmont, USA
A.J. Franzluebbers and J.A. Stuedemann 168

Hedgerow barriers and other reduced-risk controls for managing Oriental fruit moth, *Grapholitha molesta* (Busck) (Lepidoptera: Tortricidae) in apples
Carlos Garcia-Salazar, Larry J. Gut and Mark E. Whalon 181

A multi-criteria evaluation of the environmental performances of conventional, organic and integrated olive-growing systems in the south of Spain based on experts' knowledge
Carlos Parra-López, Javier Calatrava-Requena and Tomás de-Haro-Giménez 189

Vegetable crop emergence and weed control following amendment with different *Brassicaceae* seed meals
A.R. Rice, J.L. Johnson-Maynard, D.C. Thill and M.J. Morra 204

An alternative way to evaluate the environmental effects of integrated pest management: Pesticide risk indicators
Thomas J. Greitens and Esther Day 213

Farm-gate nutrient balance assessment of organic dairy farms at different intensity levels in Germany
G. Haas, C. Deittert and U. Köpke 223

Yield and fruit quality response of sweet pepper to organic and mineral fertilisation
F.M. del Amor 233

Book Review 239

Cambridge Journals Online
For further information about this journal please go to the journal website at:
http://www.journals.cambridge.org/jid_RAF

CAMBRIDGE
UNIVERSITY PRESS